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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
09/839,862	04/21/2001	Chang-Hun Kim	1103	3025

7590 07/27/2005

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EXAMINER	
STEVENS, THOMAS H	
ART UNIT	PAPER NUMBER
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DATE MAILED: 07/27/2005

Please find below and/or attached an Office communication concerning this application or proceeding.

Office Action Summary	Application No.	Applicant(s)	
	09/839,862	KIM ET AL.	
	Examiner	Art Unit	
	Mary C Hogan	2123	

-- *The MAILING DATE of this communication appears on the cover sheet with the correspondence address* --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE 3 MONTH(S) FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If the period for reply specified above is less than thirty (30) days, a reply within the statutory minimum of thirty (30) days will be considered timely.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1)☒ Responsive to communication(s) filed on 21 April 2001.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims

4)☒ Claim(s) 1-22 is/are pending in the application.

4a) Of the above claim(s) _____ is/are withdrawn from consideration.

5)☐ Claim(s) _____ is/are allowed.

6)☒ Claim(s) 1-22 is/are rejected.

7)☐ Claim(s) _____ is/are objected to.

8)☐ Claim(s) _____ are subject to restriction and/or election requirement.

Application Papers

9)☒ The specification is objected to by the Examiner.

10)☒ The drawing(s) filed on 21 April 2001 is/are: a)☐ accepted or b)☒ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

11)☐ The oath or declaration is objected to by the Examiner. Note the attached Office Action or form PTO-152.

Priority under 35 U.S.C. § 119

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

a)☐ All b)☐ Some * c)☐ None of:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

* See the attached detailed Office action for a list of the certified copies not received.

Attachment(s)

1) ☒ Notice of References Cited (PTO-892)
2) ☐ Notice of Draftsperson's Patent Drawing Review (PTO-948)
3) ☐ Information Disclosure Statement(s) (PTO-1449 or PTO/SB/08) Paper No(s)/Mail Date _____.
4) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____.
5) ☐ Notice of Informal Patent Application (PTO-152)
6) ☐ Other: _____.

DETAILED ACTION

1. This application has been examined.

2. **Claims 1-22** have been examined and rejected.

Specification

3. The disclosure is objected to because of the following informalities. Appropriate correction is required.

4. Page 2, summary item 3, "by providing a providing a result..." should be corrected to read "by providing a result...".

5. Page 3, last 2 sentences, "a virtual surgery, an image..." should read, "a virtual surgery, <u>and</u> an image...".

6. Page 9-10: the description of the elements in Figure 9 do not match up with the drawing.

Drawings

7. The drawings are objected to because of the following. Corrected drawing sheets are required in reply to the Office action to avoid abandonment of the application. Any amended replacement drawing sheet should include all of the figures appearing on the immediate prior version of the sheet, even if only one figure is being amended. The figure or figure number of an amended drawing should not be labeled as "amended." If a drawing figure is to be canceled, the appropriate figure must be removed from the replacement sheet, and where necessary, the remaining figures must be renumbered and appropriate changes made to the brief description of the several views of the drawings for consistency. Additional replacement sheets may be necessary to show the renumbering of the remaining figures. The replacement sheet(s) should be labeled "Replacement Sheet" in the page header (as per 37 CFR 1.84(c)) so as not to obstruct any portion of the drawing figures. If the changes are not accepted by the examiner, the applicant will be notified and informed of any required corrective action in the next Office action. The objection to the drawings will not be held in abeyance.

8. **Figures 8 and 9** are objected to because the lines and arrows in the picture overlap the text in the drawing, making the text difficult to read.

Claim Objections

9. **Claims 3 and 13** are objected to because of the following informalities. Appropriate correction is required.

10. **Claims 3 and 13** recite the limitation "taking a photographic picture of the patient's hard tissue". "Hard tissue" was interpreted to be the internal structure of the specimen being prepared for surgery such as the bones or skeletal structure. Therefore, it is unclear how a photograph will be taken of the hard tissue. Further, the specification's explanation of Figure 1 describes that photographic pictures of the patient were taken as the picture of the soft tissue and gives no mention to a photograph taken of the hard tissue. Therefore, it is unclear as to whether the claim limitation should read "hard tissue" or "soft tissue".

Claim Rejections - 35 USC § 112

11. The following is a quotation of the first paragraph of 35 U.S.C. 112:

> The specification shall contain a written description of the invention, and of the manner and process of making and using it, in such full, clear, concise, and exact terms as to enable any person skilled in the art to which it pertains, or with which it is most nearly connected, to make and use the same and shall set forth the best mode contemplated by the inventor of carrying out his invention.

12. **Claims 10 and 17** are rejected under 35 U.S.C. 112, first paragraph, as failing to comply with the enablement requirement. The claim(s) contains subject matter which was not described in the specification in such a way as to enable one skilled in the art to which it pertains, or with which it is most nearly connected, to make and/or use the invention.

13. **Claims 10 and 17** recite the limitation "the step of generating 2-D pictures of the 3-D visualization result", however, the specification (page 5) does not give an adequate description of how this step is performed.

Claim Interpretation

14. As to the objection to **Claims 3 and 13** discussed above, in light of the description of Figure 1 in the specification, the claims were interpreted to read "taking a photographic picture of the patient's *soft tissue*".

15. **Claims 10 and 17** recite the limitation "the step of generating 2-D pictures of the 3-D visualization result", however, the specification (page 5) does not give an adequate description of how this step is performed. The specification states, "2-D pictures from various angles may be generated by

projection from the 3-D visualization…" (page 5). From this explanation, it was concluded that the 2-D pictures generated were just pictures of the model from various angles.

Claim Rejections - 35 USC § 103

16. The following is a quotation of 35 U.S.C. 103(a) which forms the basis for all obviousness rejections set forth in this Office action:

> (a) A patent may not be obtained though the invention is not identically disclosed or described as set forth in section 102 of this title, if the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would have been obvious at the time the invention was made to a person having ordinary skill in the art to which said subject matter pertains. Patentability shall not be negatived by the manner in which the invention was made.

17. The factual inquiries set forth in *Graham* v. *John Deere Co.*, 383 U.S. 1, 148 USPQ 459 (1966), that are applied for establishing a background for determining obviousness under 35 U.S.C. 103(a) are summarized as follows:

1. Determining the scope and contents of the prior art.
2. Ascertaining the differences between the prior art and the claims at issue.
3. Resolving the level of ordinary skill in the pertinent art.
4. Considering objective evidence present in the application indicating obviousness or nonobviousness.

18. **Claims 1-22** are rejected under 35 U.S.C. 103(a) as being unpatentable over Forte et al (**Forte** et al, "3D Facial Reconstruction and Visualization of Ancient Egyptian Mummies Using Spiral CT Data", ACM SIGGRAPH 99 Conference page 223, 1999), herein referred to as **Forte**, and further in view of Ross et al (U.S. Patent Number 6,608,628), herein referred to as **Ross**.

19. As to **Claims 1,11 and 18, Forte** teaches: taking pictures of the patient's hard and soft tissue **(Figures 3 and 4, page 5, item 3, page 6, item 5)**; preparing preprocessing data **(page 9, paragraph 1)**; and deriving changes in the patient's soft tissue according to the changes in the hard tissue **(page 8, second paragraph, "Our aim...", page 13, last sentence –page 14, first sentence)**.

20. **Forte** teaches that this method will be used for future developments in virtual surgery. However, **Forte** does not expressly teach the performing of virtual surgery by manipulating the patient's hard tissue making changes in the hard tissue.

21. **Ross** teaches performing of virtual surgery by manipulating the patient's hard tissue making changes in the hard tissue **(column 4, lines 23-26,33-42)**, which includes a reconstruction unit for the generation of 3-D images to prepare preprocessing data necessary for virtual surgery **(column 4, lines 58-61)**, wherein the service of a virtual surgery center is used that is connected to a doctor through a network **(Figure 2, element 22 and description, Figure 12A and description)**.

22. Since **Forte** teaches that the method of deriving changes in the soft tissue as a result of changes in hard tissue can be used in virtual surgery, it would have been obvious to one of ordinary skill in the art at the time the invention was made to use the invention as taught by **Forte** in connection with the virtual surgery system as taught by **Ross** which includes the manipulation of a patient's hard tissue.

23. As to **Claims 2 and 12, Forte** teaches: the method of claim 1, wherein the step of taking data comprises the step of taking an x-ray picture of the patient's hard tissue **(page 5, section 3, paragraph 2, last sentence)**.

24. As to **Claims 3 and 13, Forte** teaches: the method of claim 1, wherein the step of taking data comprises the step of taking a photographic picture of the patient's soft tissue **(Figure 4, page 6, section 5, sentence 3)**.

25. As to **Claims 4 and 14, Forte** and **Ross** teach: the method of claim 1, wherein the step of preparing preprocessing data comprises the step of: generating a personalized 3-D model of the patient (**Forte**: page 5, section 3, paragraph 1, **Ross**: column 4, lines 58-62).

26. As to **Claims 5 and 15, Forte** teaches: the method of claim 4, wherein the step of generating a personalized 3-D model comprises the steps of: extracting an outline of the patient by overlaying the hard tissue picture and the soft tissue picture and extracting feature points of the patient by overlapping the outline onto a standard model containing outlines and standard feature points of a representative person **(page 6, section 5, page 13-page 14)**.

27. As to **Claims 6-8, Ross** teaches: the method of Claim 1, wherein the step of manipulation includes cutting, displacing and rotating the hard tissue **(column 4, lines 33-38)**.

28. As to **Claims 9 and 16, Ross** teaches: the method of Claim 1, further comprising the step of visualizing the result of the virtual surgery in 3-D **(column 11, lines 5-8, lines 22-29)**.

29. As to **Claims 10 and 17, Forte** shows generating 2-D pictures of the 3-D visualization **(Figures 19 and 25)** wherein the model is shown from various angles.

30. As to **Claim 19, Ross** teaches: the method of claim 18, wherein the network is the Internet **(column 12, lines 31-34)**.

31. As to **Claims 20-22, Ross** teaches: wherein the virtual surgery center has a virtual surgery consulting group for providing consulting service related to virtual surgery **(column 11, lines 22-34)** wherein the group of doctors using this system can include an orthodontic dentist or plastic surgeon.

Conclusion

32. The prior art made of record, see PTO 892, and not relied upon is considered pertinent to applicant's disclosure, careful consideration must be given prior to Applicant's response to this Office Action.

33. Any inquiry concerning this communication or earlier communications from the examiner should be directed to Mary C Hogan whose telephone number is 571-272-3712. The examiner can normally be reached on 7:30AM-5PM Monday-Friday. If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Kevin Teska can be reached on 571-272-3716. The fax phone number for the organization where this application or proceeding is assigned is 703-872-9306. Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free).

Mary C Hogan
Examiner
Art Unit 2123

L. P. Picard

LEO PICARD
SUPERVISORY PATENT EXAMINER
TECHNOLOGY CENTER 2100

Notice of References Cited	Application/Control No. 09/839,862	Applicant(s)/Patent Under Reexamination KIM ET AL.	
	Examiner Mary C Hogan	Art Unit 2123	Page 1 of 1

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
	A	~~US-5,882,206~~	~~03-1999~~	~~Gillio, Robert G.~~	~~434/262~~
	B	US-6,538,634	03-2003	Chui et al.	345/156
	C	US-5,854,850	12-1998	Linford et al.	382/128
	D	US-6,608,628	08-2003	Ross et al.	345/619
	E	US-5,267,154	11-1993	Takeuchi et al.	345/473
	F	US-6,535,215	03-2003	DeWitt et al.	345/473
	G	US-6,016,148	01-2000	Kang et al.	345/622
	H	US-6,031,539	02-2000	Kang et al.	345/419
	I	US-6,052,132	04-2000	Christian et al.	345/474
	J	US-			
	K	US-			
	L	US-			
	M	US-			

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	Forte et al, "3D facial reconstruction and visualization of ancient Egyptian mummies using spiral CT data", ACM SIGGRAPH 99 Conference page 223, 1999
	V	Fox, Robert. Association for Computing Machinery. Communications of the ACM. New York: Dec 1993. Vol. 36, Iss. 12; p. 11 (2 pages)
	W	Sourina et al, "Virtual Orthopedic Surgery Training on Personal Computer", International Journal on Information Technology, Volume 6, No. 1, May 2000
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

3D facial reconstruction and visualization of ancient Egyptian mummies using spiral CT data
Soft tissues reconstruction and textures application

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*** CNR (National Research Council) ITABC (Institute of Technologies Applied to Cultural Heritage)

**** CINECA-VISIT (Centro Interuniversitario di Supercalcolo - Laboratorio di Visualizzazione scientifica), Casalecchio sul Reno Bologna

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Introduction

The problem of rebuilding a face from human remains has been, until now, especially relevant in the ambit of forensic sciences, where it is obviously oriented toward the identification of otherwise unrecognizable corpses; but its potential interest to archaeologists and anthropologists is not negligible. We present here the preliminary results of a joint research among the University of Pisa, the Visualisation Laboratory of CINECA (Bologna) and the CNR-ITABC (Institute of Technologies Applied to Cultural Heritage, National Research Council, Rome) whose aim is reconstructing, through Spiral Computed Tomography data and virtual modelling techniques (in our case with VTK software), 3-D models of the possible physiognomy of ancient egyptian mummies. This work is carried out through a multidisciplinary approach, involving different competences: image processing, anthropology, egyptology, computing archaeology.

State of the art

The application of radiological techniques to Egyptian mummies has a very old and glorious tradition: the first reports of a radiological investigation of an Egyptian mummy was published by Petrie in 1898 [1]. Since then, radiological techniques were increasingly used and appreciated throughout the 20th century, as a non-invasive mean of investigation: egyptological, anthropological and paleopathological information could be obtained without disturbing the mummy?s wrappings. The advent of Computed Tomography in the 1970?s marked a further milestone in the history of mummies? investigation: CT numbers allowed a very fine discrimination between materials with different densities, providing an enormous amount of information not only about the mummy and its skeleton, but also about the artifacts buried with the mummy and its coffin [2]. Compared to traditional x-ray techniques, multiple axial images displayed in a clearer way the different details of cartonnage, wrappings, amulets and internal organs of a mummy [3], and allowed easy measurements of exact distances between objects inside or outside the mummy. Since the middle of 1980?s new developments in computer technology enabled the three-dimensional displaying of axial CT images. The new application, born for clinical use and especially developed for assisting in the planning of surgical operations, was soon extended to mummies examinations and imaging [4]. In the last years, spiral CT has considerably enhanced clinical imaging. The use of this new technique has furtherly widened the range and quality of possible investigations on egyptian mummies.

The research project

The impulse to our research, born in the ambit of the collaboration between the egyptologists of the University of Pisa and the anthropologist Francesco Mallegni, originated in the observation that no previous work dealt with the complex problem of repositioning soft tissues on the generated model of the skull. Computerized reconstructions stopped there where soft tissues started. Previous works were not specifically interested in the problem of physiognomic reconstruction, but, when even the interest existed and plastic models of the mummy?s head were produced, by stereolithography or by hand, the final moulding of soft tissues was essentially a "human matter", the joint result of the anthropologist?s expertise and the artist?s sensibility [5]. A similar method was already experimented by F. Mallegni for the reconstruction of a model of the head of the prince Wadje, whose tomb (about 2000 b.C.) was descovered by the mission of the University of Pisa, directed by Edda Bresciani [6].
The need for an automatic, fast and scientifically based program for the reconstructions of mummies (and human remains) features started the collaboration with the Laboratory of Visualisation of CINECA, involved in research both

on archaeological visualisation and biomedical imaging.
Focussing on the problem of facial reconstruction, we choosed a mummified head in good condition, from the Egyptian Section of the Archaeological Museum in Florence (inv. N. 8643). The date of its acquisition is 1893; we lack any other reliable information about its provenance. C14 calibrated dating of a sample of the hair gave a probability distribution between 339 b.C. and 201 b.C. [7]. The very good condition of the head, attesting the quality of the embalming process, make us prefer the higher dating.

Fig. 1 The mummified head in Florence (inv. N .8643) (Soprintendenza Archeologica della Toscana)

Project Planning

The project involved five different stages:

1. anthropological and egyptological analysis of the head;

2. spiral CT of the head;

3. reconstruction of a 3-D model of the skull generated from CT data processing;

4. reconstruction of soft tissues;

5. application of textures fitting the somatic features.

The different stages are not strictly sequential: as we shall see, spiral CT scannings and, later, their 3-D reconstruction

provided new interesting data to the previous phases (anthropological and egyptological investigations).

First phase of research: preliminary anthropological results

1. The anthropological study of the mummified cranial remains allowed us to identify a male subject with an age at death of around 40 years. The skull is dolichocranic, of medium height in norma lateralis, and with rounded occiput, narrow face, high cheekbones, gracile even if well developed in its height, jaw; the orbits are narrow, the nose is well-shaped, and of Europoid look.

The general appearance of the subject, especially regarding the face and the shape and structure of his hair, lead us to exclude Negroid influences, but closely resembles present and past Berber ethnic characters.

The very good conservation of the head pointed to an individual high in the social hierarchy, so as to grant himself an effective (and expensive) embalming process.

2. The mummy was scanned on 18th April 1997, using a Siemens Somatom Plus 4 spiral computer tomography scanner at Careggi Hospital in Florence, thanks to the kind collaboration of the radiological equipe. Slices thickness was 0.5 mm through all the skull.

Fig. 2 CT scanning of the head demonstrated the post-mortem transnasal ethmoid fracture created by the embalmers to extract the brain tissue; the cranial cavity was filled with hot melted resin, later solidified, introduced with the mummy resting on its back, as the model reconstructed from the CT images clearly displays.

Embalming excerebration through the ethmoid was very common in the Late Period, practised until Ptolemaic age, as well as the filling of the cranial cavity with resin [8].
The spiral CT images were later electronically transferred to the Onyx2 workstation (Silicon Graphics) at CINECA for post-processing.

3. In the methodology used for 3-D reconstructions generated by spiral CT data sets, CT slices must be stacked up and interpolated in order to build a volume. Once created a volume, it is possible, by means of suitable algorithms, to generate surfaces whose points have the same function value. They are called *isosurfaces*. A popular algorithm for determining isosurfaces is the so called *marching cubes* [9] , the same used in the 3-D reconstruction of our mummy?s skull. The principle underlying the application of this algorithm to the kind of problem here described is that similar materials have the same radio-opacity and are, consequently, represented in a CT scan by the same densitometric level. In CT slices, the intensity associated to each pixel in the grey-scale is proportional to tissues density: black corresponds to air, white to bones. It is therefore possible processing the CT scans sequence so as to obtain a 3-D grid, where to each "knot" (control point) is associated the densitometric value measured by the CT scans. The result is a 3-D 256 grey levels image.

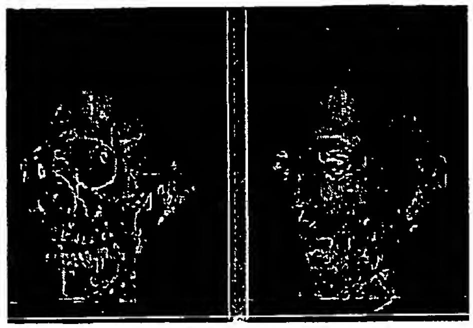

Fig. 3 a) hard tissues b) external surface

This phase of the work was particularly interesting from the anthropological perspective: the use of this technique allowed us to visually exclude the mummified soft tissues and directly observe the cranial bones with a very high image resolution. This method offered also the chance of a morphological and morphometric check of the anthropologist?s observations on the specimen (covered by the disseccated soft tissue): these two methods of investigation led to the same diagnosis of Berber group.
The image of the skull gave us the chance to observe, directly on the cranial vault, a bone pathology and a biological answer to the pathogenic factor that shows a long survival of the subject. X-ray examination of the mummified skull showed in more detail the reactions to this kind of pathology so that we could perform a global analysis of the sample.

4. This stage of our work is still in a preliminary phase. Among the possible methodologies to deal with this complex problem, we focussed two different promising ways:

> **A.** implementation of the anthropologists? protocols developed to the reconstruction of soft tissues on the skull;
> **B.** use of *warping* techniques.

A. Generally, the anthropological methodology to reconstruct soft tissues on a skull is borrowed from forensic sciences: as it is well known, the thickness of the soft tissues is reconstructed on the bones through the use of pegs at marked points. All the pegs are joined by strips of plastiline of fixed thickness and the empty spaces among them are then slowly filled with mouldable material: in this way, it is possible to reconstruct nearly all the face that belonged to the living subject; on this, nose cartilage, eye globes and lips are added; because the orbicular muscles around the lips leave no impressions on the jaw bones, it is important to consider for their modeling the ethnic group to which the subject belonged. The markers helping in the reconstruction are based on anthropology and forensic studies of people of varying ages and populations. Their number may vary in the different protocols which anthropologists follow: as for the model of Wadje?s head, Francesco Mallegni?s reconstruction was based on the method described by Douglas H. Ubelhaker, following Rhine and Campbell?s tables (1980) and Rhine, Mooer and Weston?s (1982) [10]. Though this method has a certain degree of subjectivity, nevertheless it is sufficiently reliable. A software implementation of the above mentioned protocols could assist the operator in locating the markers on the 3-D model of the skull by a graphic interface, so as to choose the correct set of anthropological parameters. Subsequently, interpolation methodologies could carry out automatically the soft tissues growing.

B. A different method consists in the distortion (warping) of the 3-D model of a reference scanned head, until its hard tissues match those of the mummy. The subsequent stage is the construction of the hybrid model composed by the hard tissues of the mummy plus the soft ones of the reference head [11].
We believe that very good results could outcome through a semiautomated interactive procedure, integrating the two methodologies here described.

5. While hard and soft tissues give morphological information, textures provide colours and aesthetical features. They are "pasted" over the 3D models by means of mapping procedures. In this preliminary phase we used as texture the photograph of a modern Berber, published in an anthropological treatise [12], well fitting the general somatic features of our reconstruction but, unluckly, of very low resolution **(fig. 4)**. Moreover, being a frontal view, it does not give sufficient information for the mapping of the entire model.

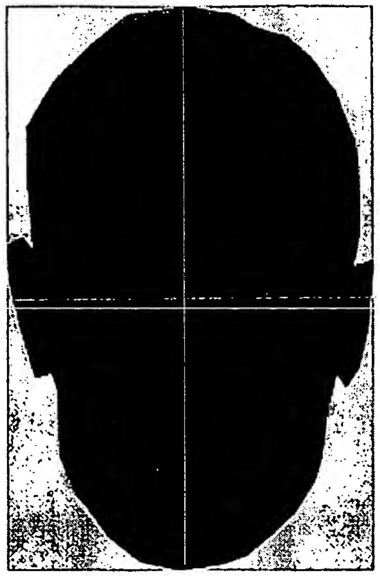

fig.4

The texture was mapped onto the 3D model to perfectly match the frontal view of the mummy but it loses its grain as soon as we depart from the frontal view. Much better results could be obtained with different high resolution views of a new subject.

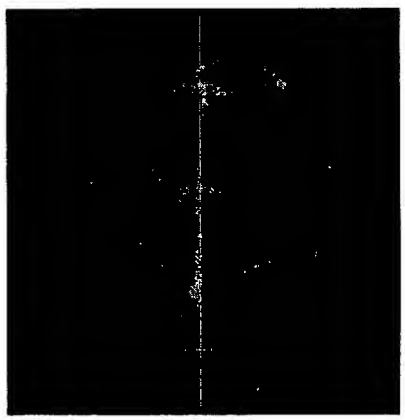

Fig.5 The texture, suitably processed and coloured, is mapped onto the 3-D model.

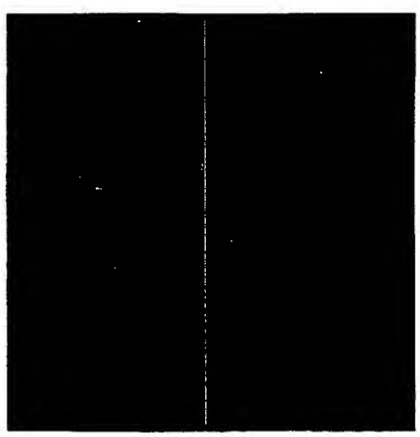

Fig. 6 Lateral view

Development of the project: soft tissue reconstruction using VTK

After a first part of work, our open problem is to reconstruct the lacking elements of a 3D digital model generated from CT scans applied to a mummified cranial remains (Fig.7)
As we have described in the previous part of the paper, [14] we work with an hybrid approach [13];

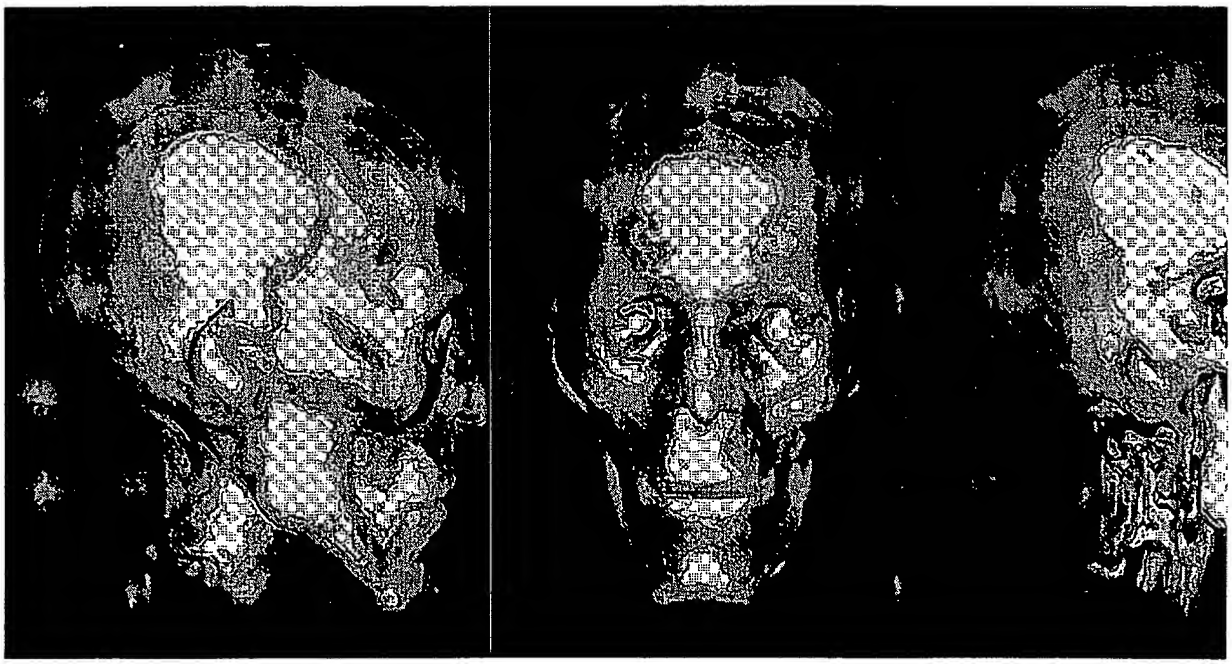

Fig.7 Digital model of the mummy: surfaces corresponding to soft (lef

on one hand there is the implementation of anthropologists? protocol (also known as ?Manchester protocol?) [15], used in manual reconstruction of remains, in order to control the thickness of soft tissues at specific positions in accord to the measures indicated in [16]. On the other hand warping techniques allow to enhance the mummy model with information coming from another complete CT scanned head of the same race, with the right properties according to anthropological studies, used as reference model.
Our aim is to obtain a perfect match among hard tissues so that soft tissue of reference model can be used to represent those of the mummy with a good approximation.
Moreover we are developing a tool in order to apply to the model cylindrical textures obtained multiple views of a well suited individual or from other sources as sculptures and paintings.
Software implementation has been designed using Vtk (The Visualization ToolKit) [17], a public domain library for scientific visualization in order to guarantee performance and portability.

Soft tissues reconstruction

As shown in fig.8, our methodology may be subdivided in different working steps that we are going to explain deeply.

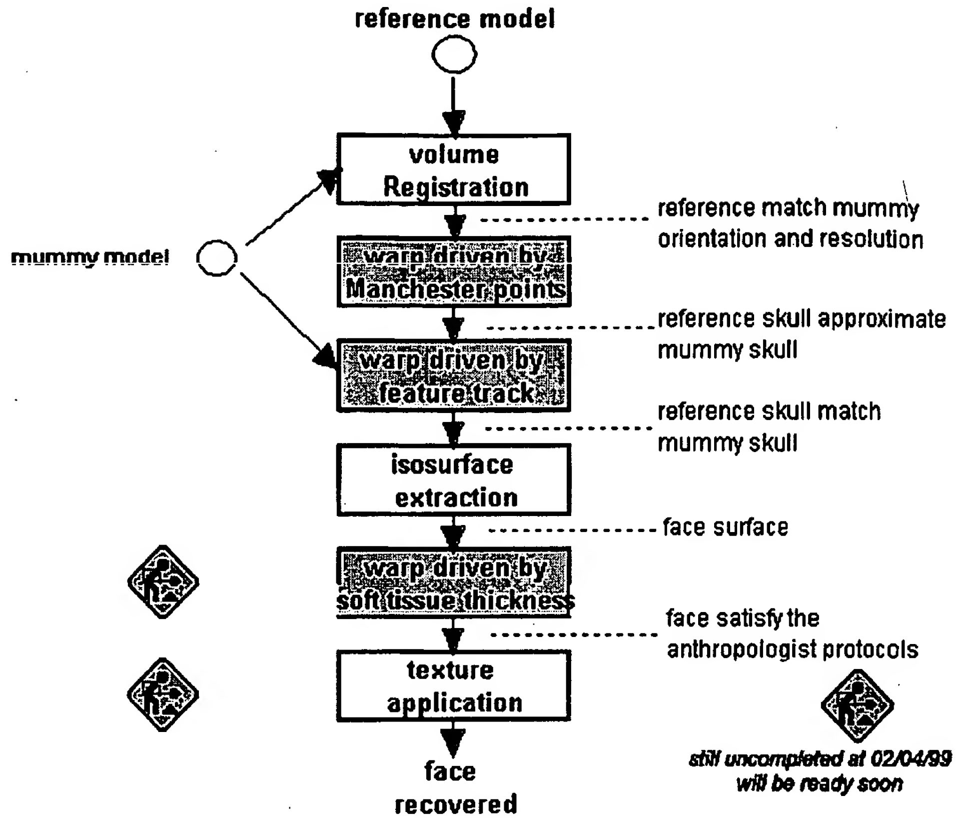

Fig.8 The different steps of soft tissue reconstruction

For the following steps to work correctly CT scans data representing our model and mummy should have the same placing, orientation, dimensions and resolution. This is generally not true especially when dealing with data coming from different machine so the first step is to perform a manual registration (Figure 3), that is a rigid transformation, among volumes in order to work in the same system of coordinates. Software like AIR [18] are also available for automatic registration but sometimes, especially when volumes are quite different, they do not produce satisfactory results.

As further requirement greyscales of hard tissues must be similar, in spite of different methodologies of acquisition though mummy?s tissues has been deteriorated. It is possible to correct these differences shifting and scaling intensities using histogram information (Fgs.9-10).

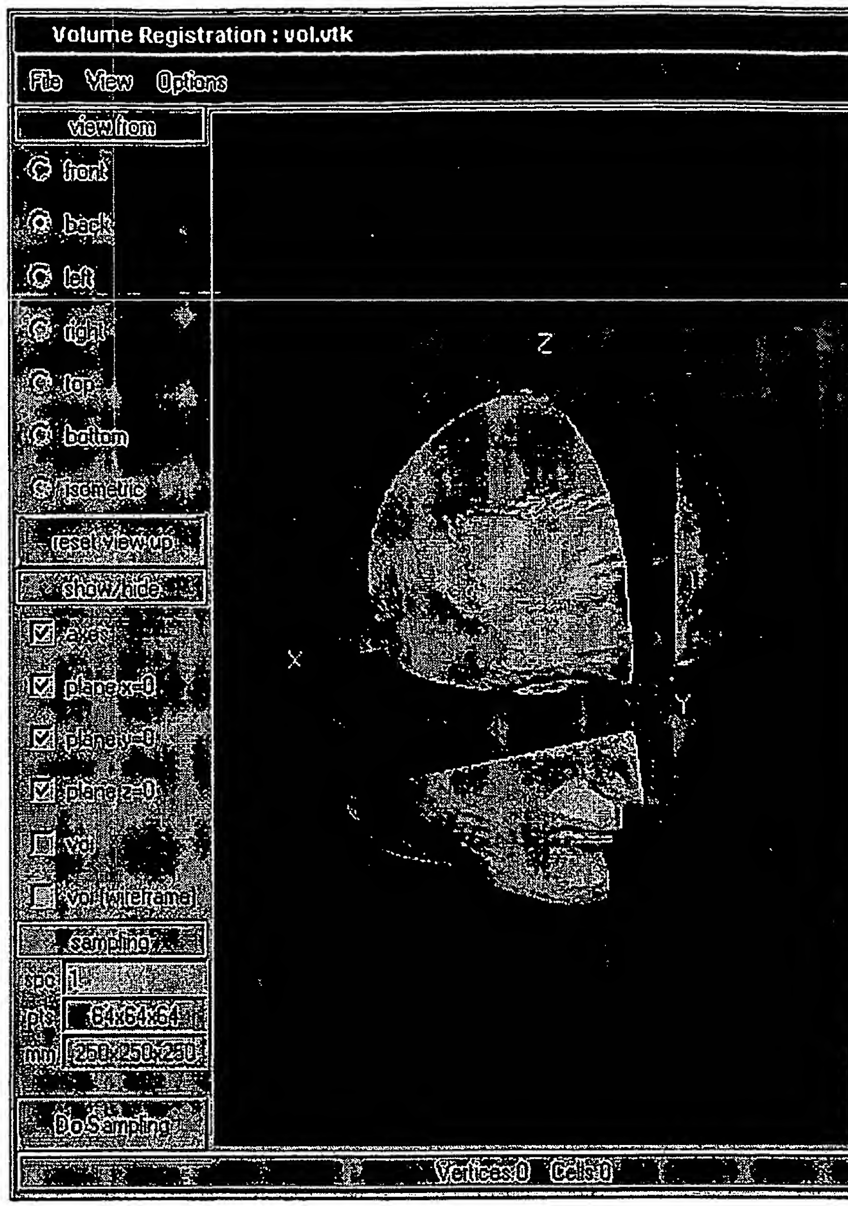

Fig.9 Interface of the registration program

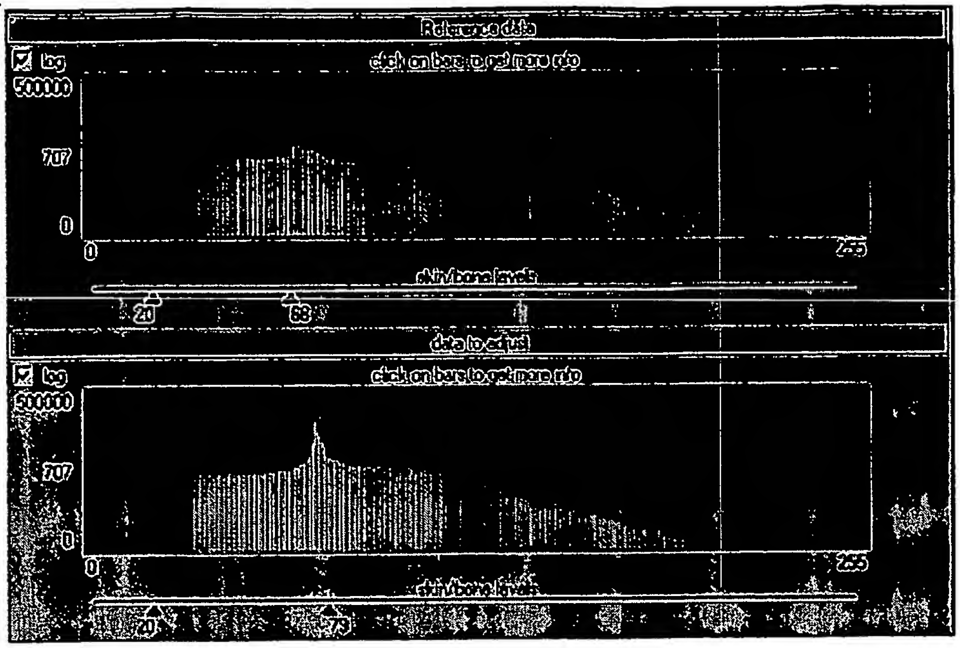

Fig.10 Hystogram of mummy and model dataset

We outline that we prefer to transform the reference model to preserve original data of the mummy.

For volume resampling, smoothing (to remove aliasing phenomena) and surface generation Vtk internal facilities are used.

We usually take into account isotropic volumes with squared voxel of 1 mm as trade-off between performance and image quality.

At this point we proceed with the setup of the Manchester pegs (see Appendix A) onto the surface of the hard tissues of the mummy (fig.13) while for the reference model it can be predetermined (fig.14). The aim of these phase is to fix some constraints for the resulting physiognomy and to provide a first guess for the following step that is the *features tracking*.

Pegs are mapped onto a spherical surface of parametric ratio, so that the user can place quickly the whole set and the adjust single pegs.

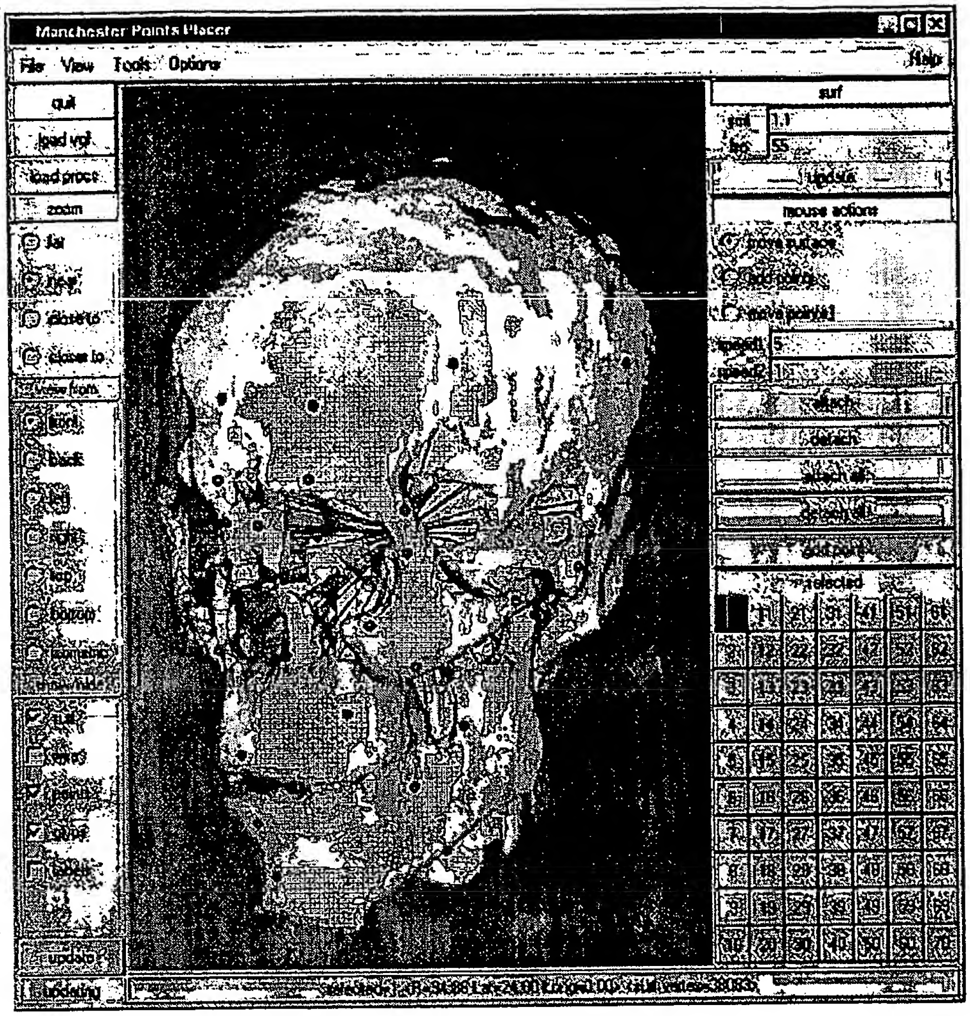

Fig.11 Manchester points placed over the mummy

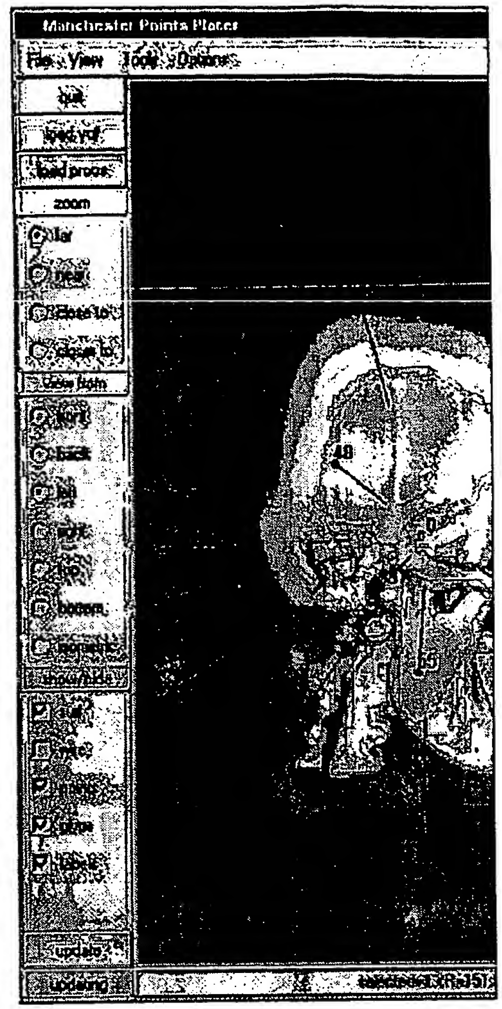

Fig.12 Bringing the

Calculating vector displacement among couples of corresponding points we obtain a scattered field to drive a first warp phase (fig. 11).

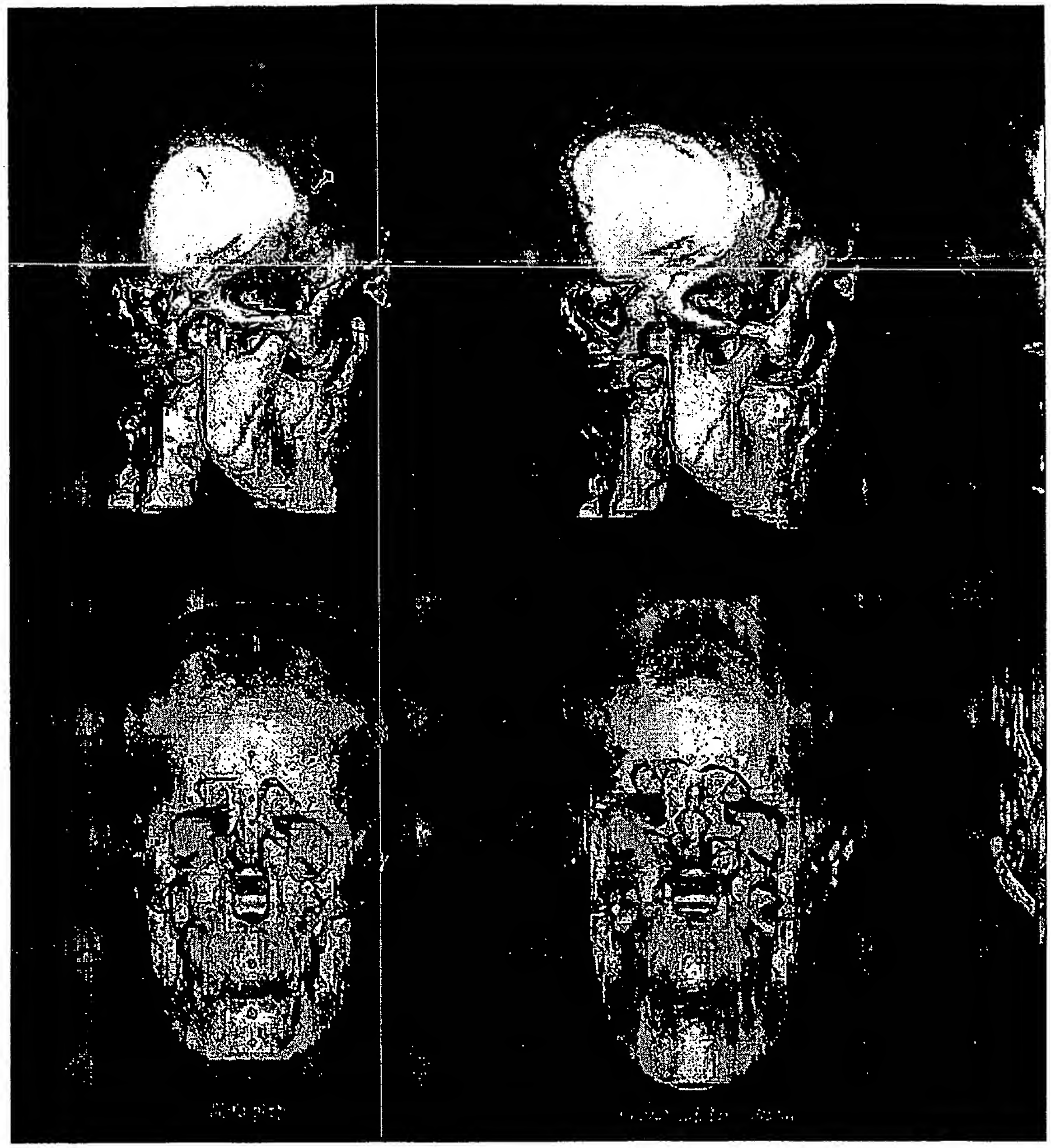

Fig.13 Warp driven by Manchester points

In the next stage we proceed to a warp driven by a features tracking (fig. 13).
Features tracking consists in determining a correspondence between sets of characteristic points pertaining to the volumes in order to obtain a scattered motion field with more details.
Initially this set of points is chosen as a subset of points that are vertices of hard tissues surface of the mummy; some of these points, with particular characteristics, are identified as features.
If, consecutively a test, a feature is retained reliable (fig. 14), we search the corresponding position in the reference volume. If the result is good, the resulting motion field is defined among subsets of bone surfaces, from the reference model to the mummy volume (fig. 15).
Once generated a scattered motion field, it must be diffused within the whole reference volume. This is performed using Shepard method [19] available in Vtk (details are in Appendix B).
Diffused motion field can be used to warp (one more time using vtk facilities) every structure pertaining to reference model coherently with mummy model (figures 16 and 17); therefore we reconstruct mummy soft tissues warping those of reference model (fgs. 15-19).

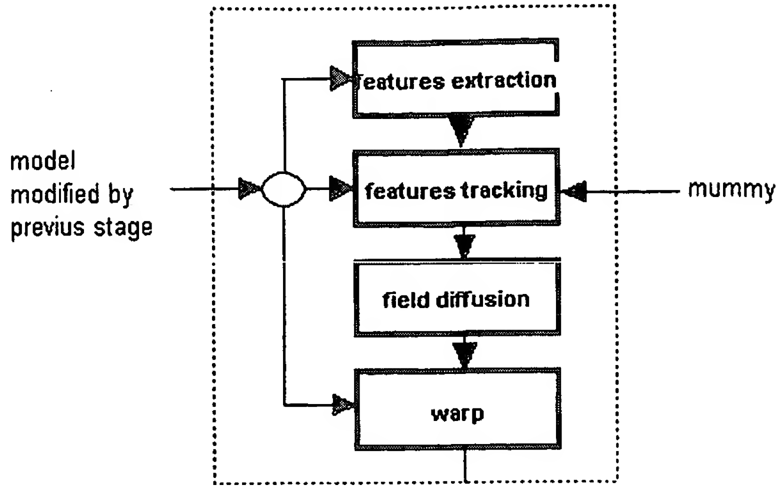

Fig.14 Building blocks for this stage

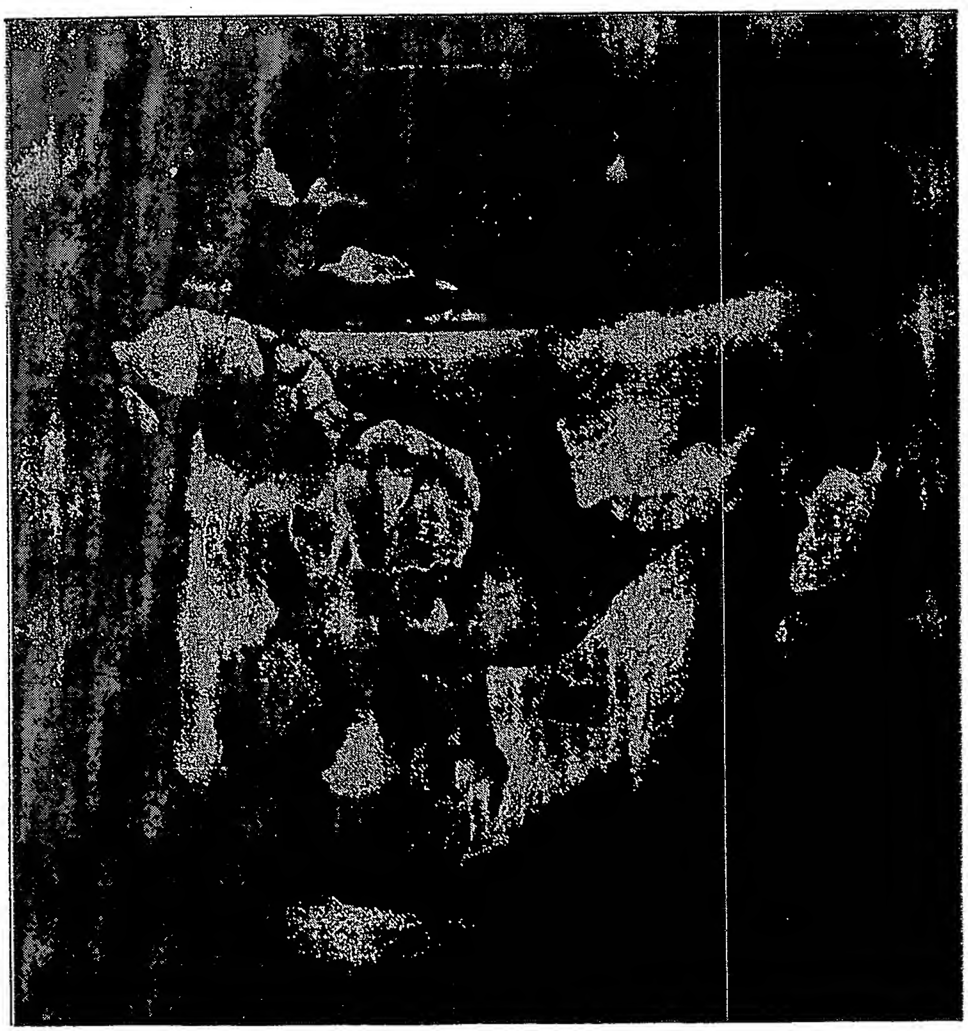

Fig.15 Points on isosurface of bone are used as feature points. Colors represent the reliability values

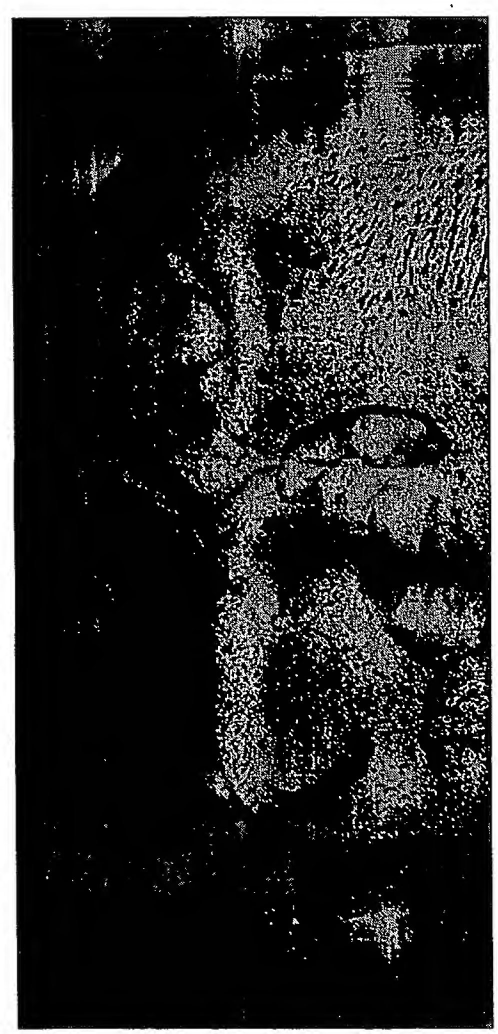

Fig.16 An example of a scattered fi

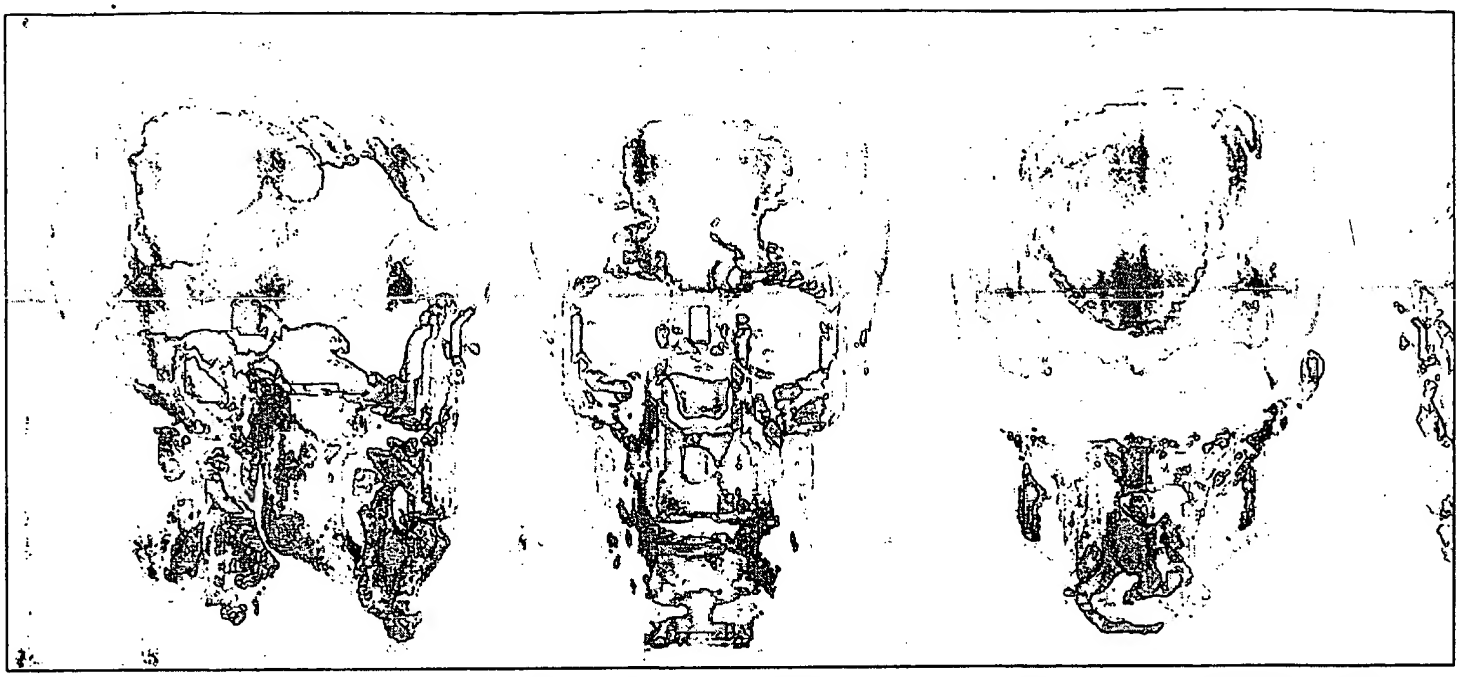

Fig.17 Model skull (blue) after this stage overlapped with mummy skull (white)

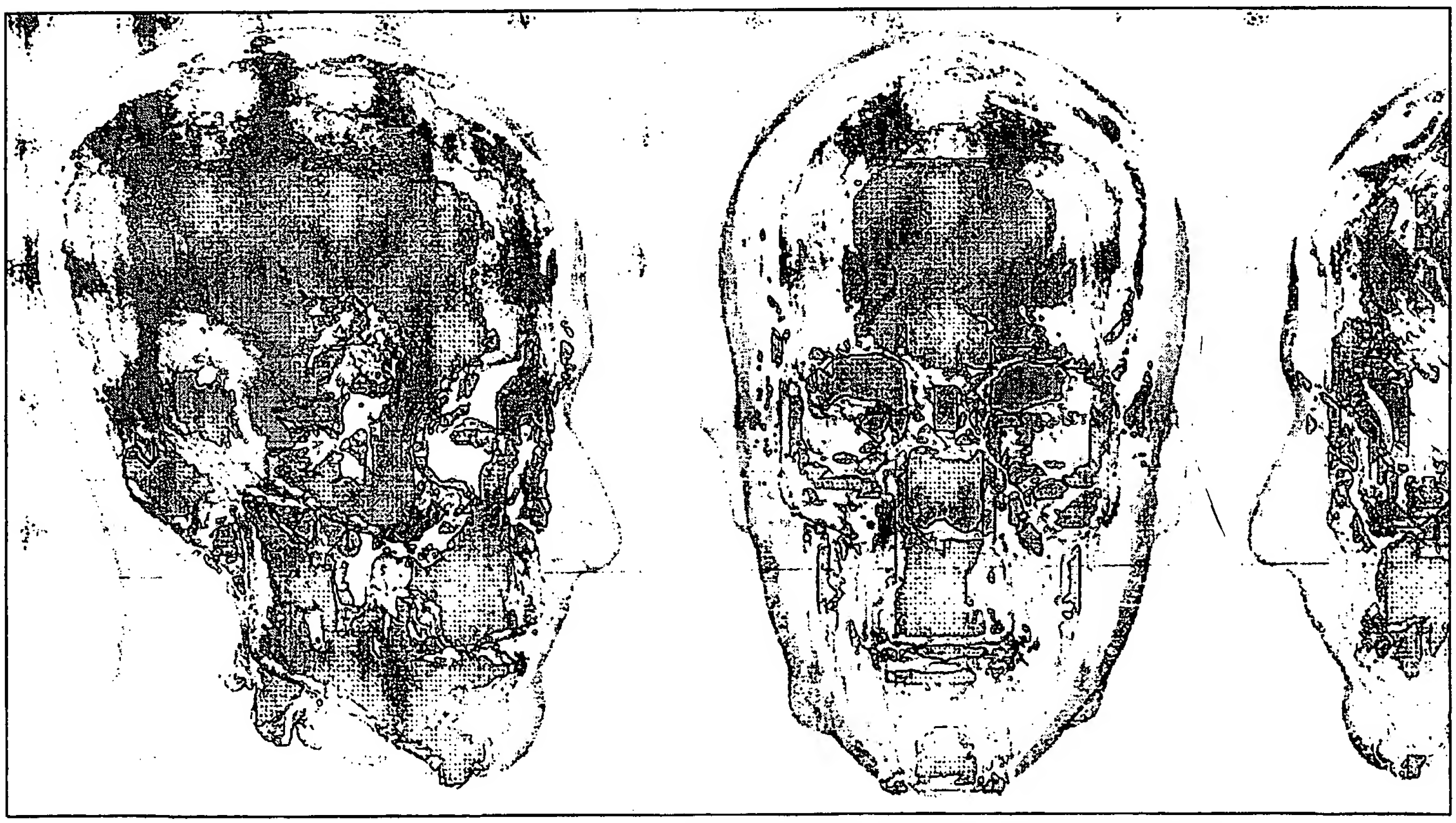

Fig.18 Model skin (blue) and mummy skull (white)

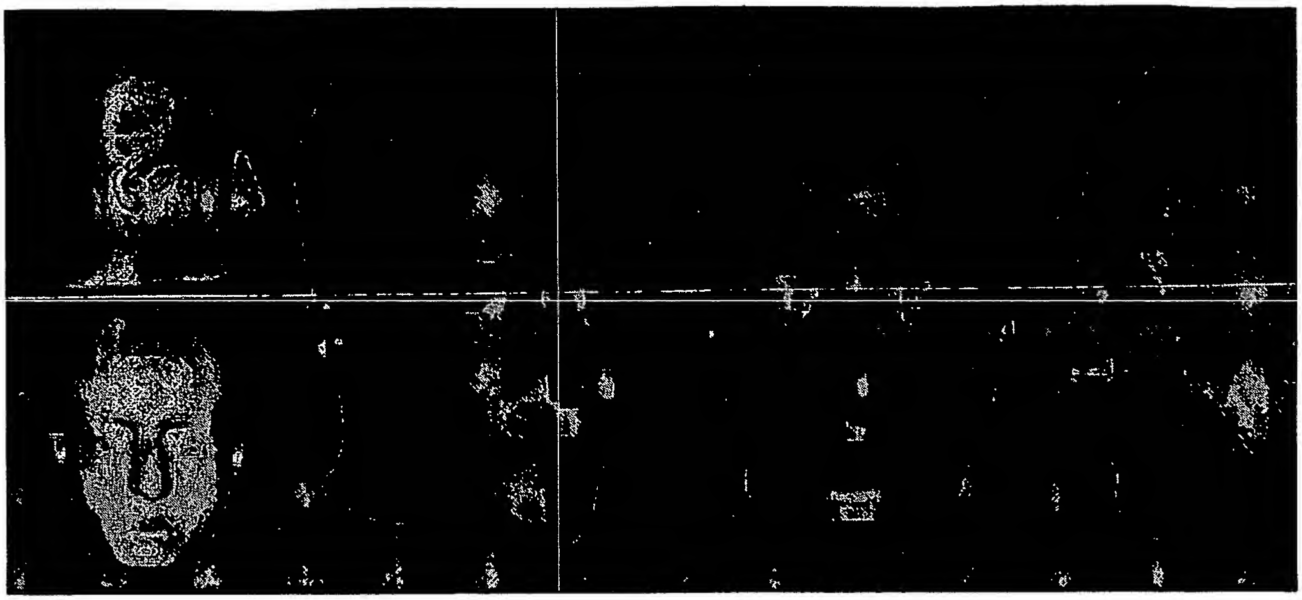

Fig.19 Face generated

Theory of this algorithm (we will go through a brief explanation) is taken from [20] as a rework of Lukas-Kanade algorithm [21]. We have adapted this algorithm to our requirements and built a vtk filter.
We consider the relation between hard tissues surface of the reference model and hard tissue surface of the mummy as a continuos deformation in the time.

If $E\left(x,y,z,t\right)$ is the intensity of a point of coordinates *(x,y,z)* at time *t* in the mummy volume and $\mathbf{V}=\left(u(x,y,z),v(x,y,z),\mathrm{w}(\mathrm{x},\mathrm{y},\mathrm{z})\right)\equiv\left(u,v,w\right)$ is the motion field, where $u(x,y,z)$, $v(x,y,z)$ e $w(x,y,z)$ are components in *x*, *y* e *z* directions of velocity vector, we suppose that the intensity function is the same at the time $t+\delta t$ in the point $\left(x+\delta x,y+\delta y,z+\delta z\right)$ of the reference model, where $\delta x=u\delta t$, $\delta y=v\delta t$ e $\delta z=w\,\delta t$ and $\delta t\rightarrow 0$.

(1) $$E\left(x+u\delta t,y+v\delta t,z+w\delta t,t+\delta t\right)=E\left(x,y,z,t\right)$$

If the intensity function change smoothly with *x*, *y*, *z* e *t*, we can manipulate the equation (1) with Taylor?s series to obtain

(2) $$E(x,y,z,t)+\delta x\frac{\partial E_r}{\partial x}+\delta y\frac{\partial E_r}{\partial y}+\delta z\frac{\partial E_r}{\partial z}+\delta t\frac{\partial E_r}{\partial t}+e=E(x,y,z,t)$$

where *e* contains terms in δx, δy, δz e δt higher than first order.

Eliminating $E\left(x,y,z,t\right)$, rationing by δt, and calculating limit for $\delta t\rightarrow 0$, we obtain

(3) $$\frac{\partial E}{\partial x}\frac{dx}{dt}+\frac{\partial E}{\partial y}\frac{dy}{dt}+\frac{\partial E}{\partial z}\frac{dz}{dt}+\frac{\partial E}{\partial t}=0$$

that is the totally derivative of E in the time.

(4) $$\frac{dE}{dt} = 0$$

Using abbreviated notation:

$$u = \frac{dx}{dt}, \qquad v = \frac{dy}{dt}, \qquad w = \frac{dz}{dt},$$

$$E_x = \frac{\partial E}{\partial x}, \qquad E_y = \frac{\partial E}{\partial y}, \qquad E_z = \frac{\partial E}{\partial z}, \qquad E_t = \frac{\partial E}{\partial t},$$

we can write the 3 as

(5) $$E_x u + E_y v + E_z w + E_t = 0$$

known as *motion field constraint equation*, where E_x, E_y, E_z ed E_t are partial derivatives.

We say that **x** is a *reliable feature* if

(6) $$\tau_{\min} \le \sigma_{\min}\left(\int_{W(x)} \nabla I \nabla I^{T} dx dy dz\right) \le \tau_{\max}$$

where:

$I(\mathbf{X}, t)$ is the matrix of intensity function E in the point $\mathbf{X}$ =(x,y,z) in the region W(**x**) at the time t;

∇ is the gradient operator;

σ min(Ψ) represents the smaller eigenvalue of matrix Ψ ;

$\tau_{\min}, \tau_{\max}$ are predetermined thresholds.

We consider a window $\tilde{W}$ (q) centered in q of $wsize \cdot wsize \cdot wsize$ dimensions.

We represent (6) in discrete fashion

(7) $$\tau_{\min} \le \lambda_{\min}\left(\sum_{p(i,j,k)\in \tilde{W}} \nabla E \cdot \nabla E^{T}\right) \le \tau_{\max}$$

where

$$\nabla E \cdot \nabla E^T = \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} \begin{bmatrix} E_x & E_y & E_z \end{bmatrix} = \begin{bmatrix} E_x^2 & E_x E_y & E_x E_z \\ E_y E_x & E_y^2 & E_y E_z \\ E_z E_x & E_z E_y & E_z^2 \end{bmatrix}$$

The solution of (4) respect to V is given by

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = -\mathbf{M}^{-1} \cdot \mathbf{A}^{\mathrm{T}} \cdot b \tag{8}$$

where

$$\mathbf{M} = \sum_{p(i,j,k)\in W} \nabla E \cdot \nabla E^{\mathrm{T}}$$

is the 3x3 symmetric matrix that represents the term inside parenthesis of (7),

$$\mathbf{A} = \left[\nabla E(x_1), \ldots, \nabla E(x_n)\right]^{\mathrm{T}}$$

and b is a timing gradient

$$b = \begin{bmatrix} E(x_1, t + \delta t) - E(x_1, t) \\ \mathrm{M} \\ E(x_i, t + \delta t) - E(x_i, t) \\ \mathrm{M} \\ E(x_{wsize \cdot wsize \cdot wsize}, t + \delta t) - E(x_{wsize \cdot wsize \cdot wsize}, t) \end{bmatrix}$$

that is the intensity difference between reference and mummy volumes.

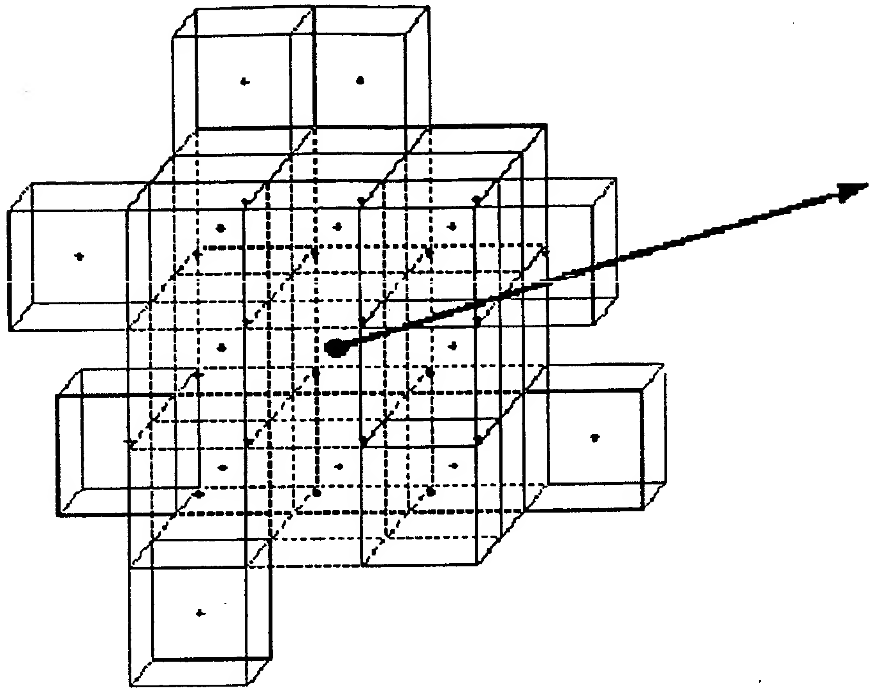

Fig.20 In this case the motion field is calculated for a 3x3x3 window and applied in his center (the feature point). Bold grid refers to the reference volume.

Normally this result is affected by an error of 10% approximately. To improve its precision we use an iterative multistep method: the window is moved in the mummy volume in the direction of estimated motion and the field is recalculated among new positions as shown in fig. 21.

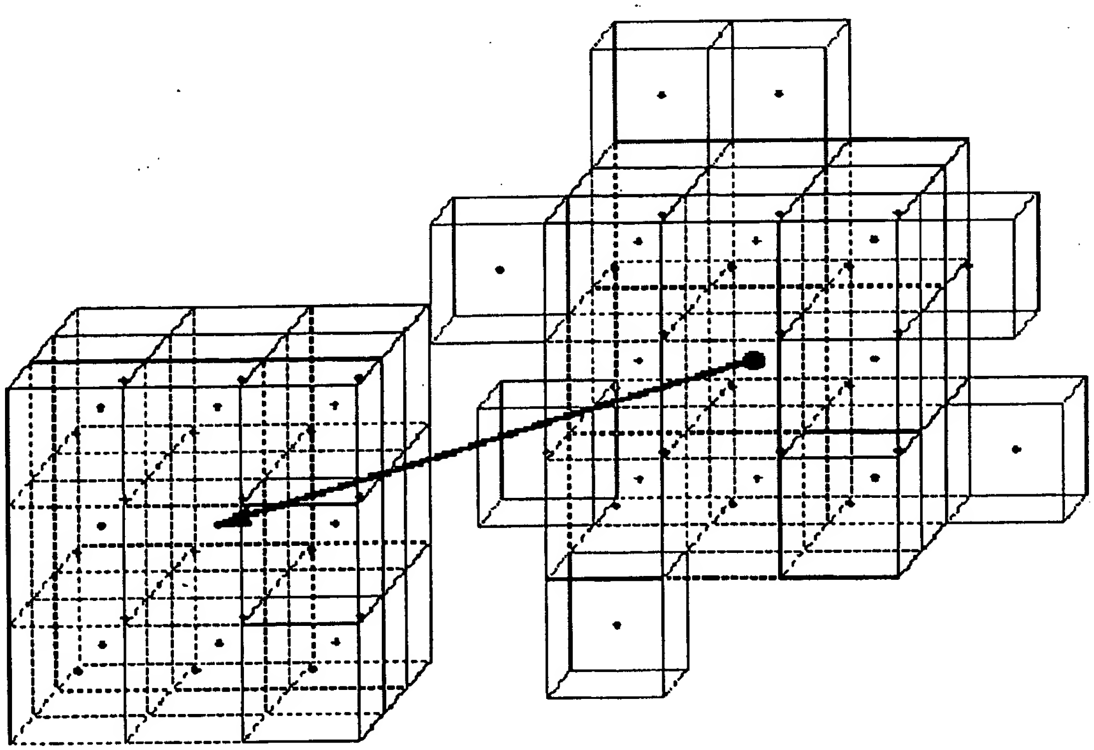

Fig.21 At every step the motion field is recalculated between new position.

The process will be over when displacements become smaller than a predetermined arbitrary constant or when a maximum limit to iterations is reached. In case of non convergence the feature is discarded.
When a feature doesn?t coincide with a voxel, window points are calculated by *trilinear interpolation* using vtk facilities (see fig. 22).

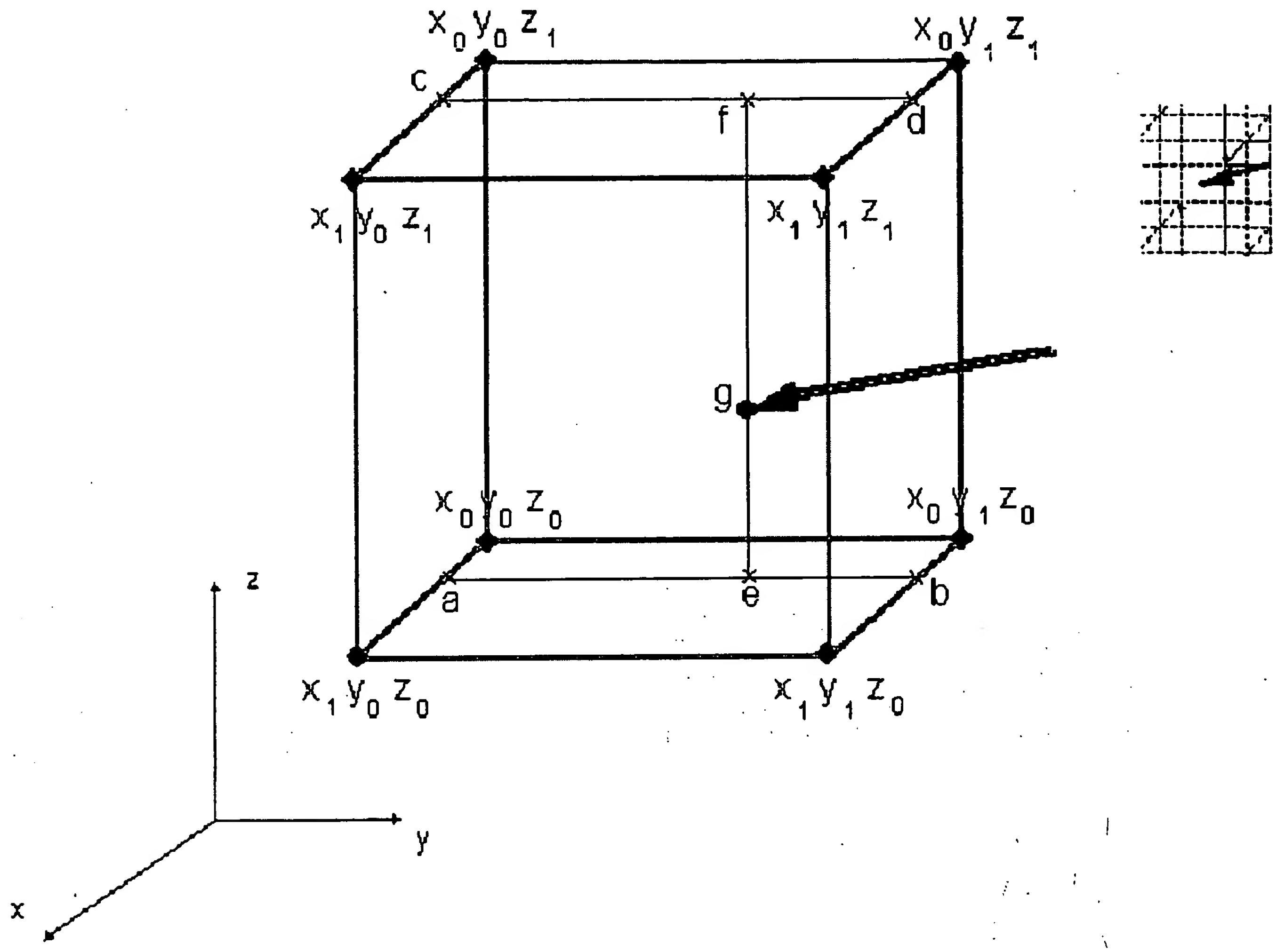

Fig.22 Intensity value is recalculated by trilinear interpolation of voxels.

As final stage of soft tissue reconstruction we present warp driven soft tissues.
In this moment this stage is still in developing so we have no picture, anyway the idea is simple: for each of the Manchester points we find its corresponding on the skin surface, in this way we can measure the actual soft tissue thickness. By consulting the thickness table we find the corresponding desired thickness measure.
Saying that the actual thickness must become the desired thickness we generate another scattered field that will drive this third warp.
This last step is performed just on the skin surface.

Texture application

We are now at summarizing mainly points of this stage, still under development, inspired by the work presented in [22].
Starting from at least three views of our candidate, as in figure 23, we will going to generate a cylindrical texture.

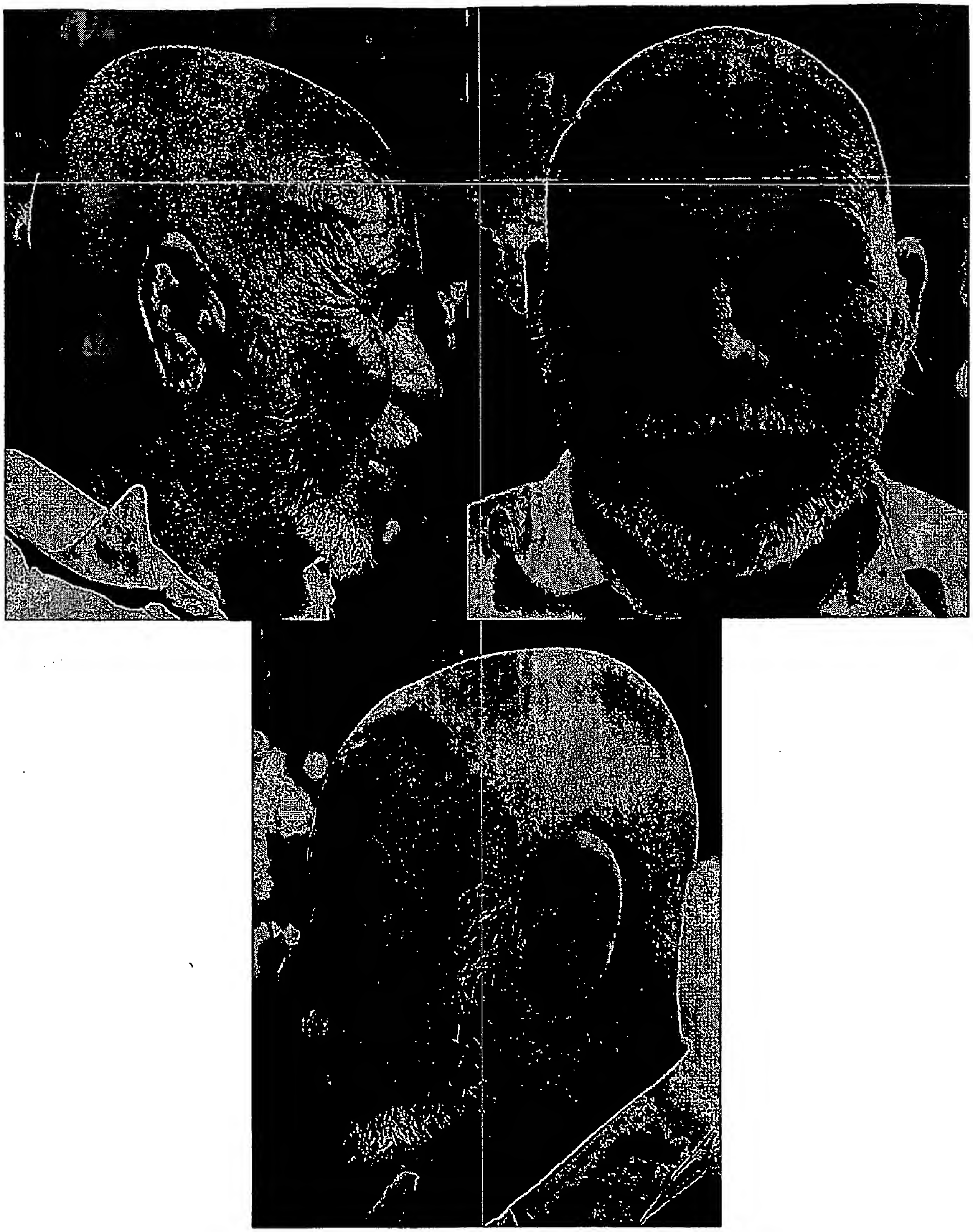

Fig.23 Several views for generating cylindrical textures

As shown in figure 24, each point P on the cylindrical texture will be projected on the cylindrical axes, intersecting a point q on the surface, watching the angle between the normal in q and the normal of the view we can determine which of the views q can see,
The color for the Point P is given by a weighted sum of the colors taken from the visible views, and the weights depend

again on the angle among the normals.
Before the extraction from the views colors has to be modified to match the corresponding projection of the whole model (fig.25), we can realize this *morph* implicitly after fixing a way to map projections in the desired points of the view.
This mapping could be achieved by projecting the Manchester points over the views and let an user move them in the right place.

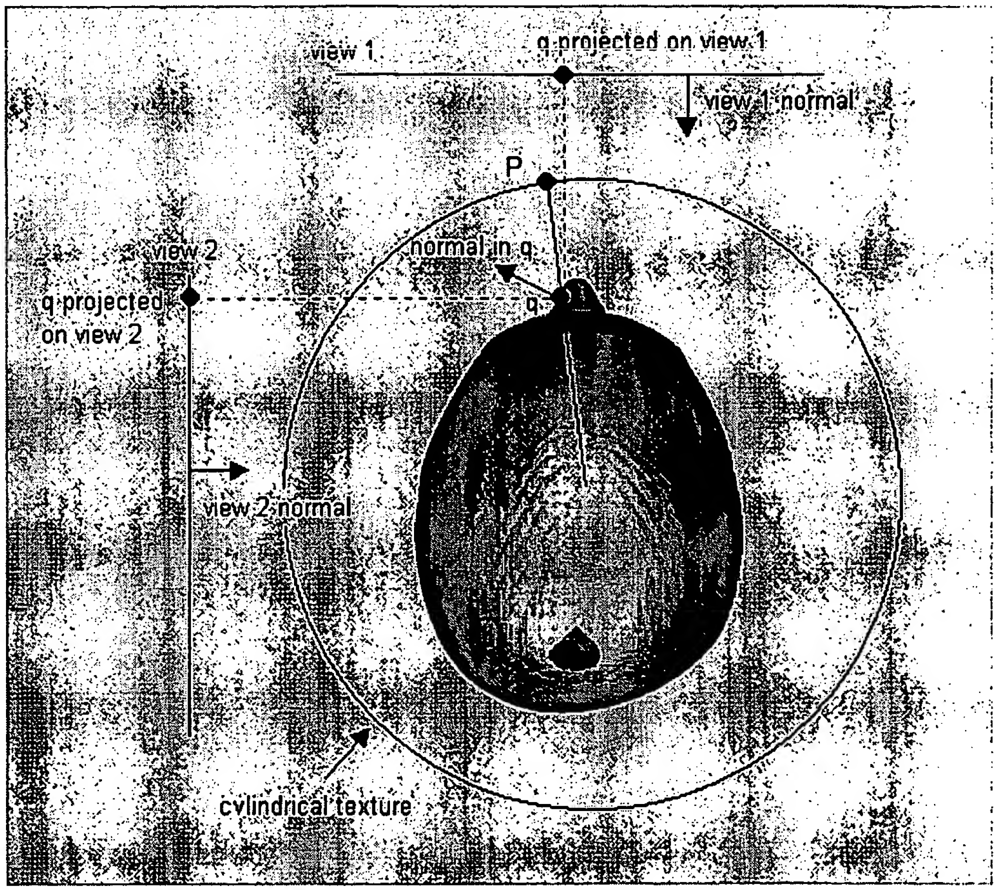

Fig.24 Creating the cylindrical texture

Fig.25 Texturized model of recontructed soft tissues of the mummy

Conclusions: the virtual model

In our project, for obtaining better performances through the virtual 3D visualisation of the reconstruction we have used the powerful workstation Onyx2 (Silicon Graphics at VISIT, CINECA), equipped with an architecture of type multiprocessor, with 4 processors R10K, 1 Gbyte of RAM, computing power of 1.5 Gflop, 1 graphic pipeline, that it can process 11 milions of polygons per second. In fact the main problem, processing a large amount of data, was to process and visualise in real time and in 3D the data volume. The
interactive way to explore and show the whole model gives the possibility to understand deep features of the data: in our case, our interdisciplinary team, constituted by archaeologists, anthropologists, and computer experts, has could discuss in real time problems and characteristics of the data comparing in detail hypotesis and interpretations about the egyptian head, anthropometric data and computer/images information. We can describe the processing as a cognitive model of the find. Finally, we have experimented the VR CrystalEyes, wireless pairs of glasses, with lenses capable of alternately shuttering in sequence with left-eye right-eye images
interlaced on a computer display; the result is a stereoscopic effect, allowing the user to view the contents of the computer display in 3D.
Possible develpoments of the project will concern:

- Integration of CT scan data and reconstructions with the egyptian iconography (i.e. ancient sculptures of the same period).
- VRML version of that kind of models.
- Images databases on line in Internet for organising a world collection of this type of data.
- Project integration with other sciences with the same aims, such as forensic sciences, virtual surgery, biology,

criminology.
- Off line multimedia version of data (i.e. on CD ROM or DVD), for publications and scientific divulgation.

Finally, although some modules are still in development and reference model was not ideal for this case of study because it is an European, we think to have obtained satisfactory results, that is an Egyptian physiognomy with some European element.
The level of automation reached in building models from CT data, reconstruction, texture application and visualization allow to the user to complete whole process in 2-3 hours on a PC or graphic workstation . Moreover we hope to reduce time consuming phases like features tracking, that could be improved experimenting others algorithms of *non-rigid registration.*

Appendix A: our set of skull markers

We have referred to the set of points illustrated onto tables by Rhine & Moore . These points, originally is in number of 32 and mainly concentrated on the face, are in green in figure 26.
For our purpose we add further points, the yellow ones (figure 27) and now we have a set of 67.

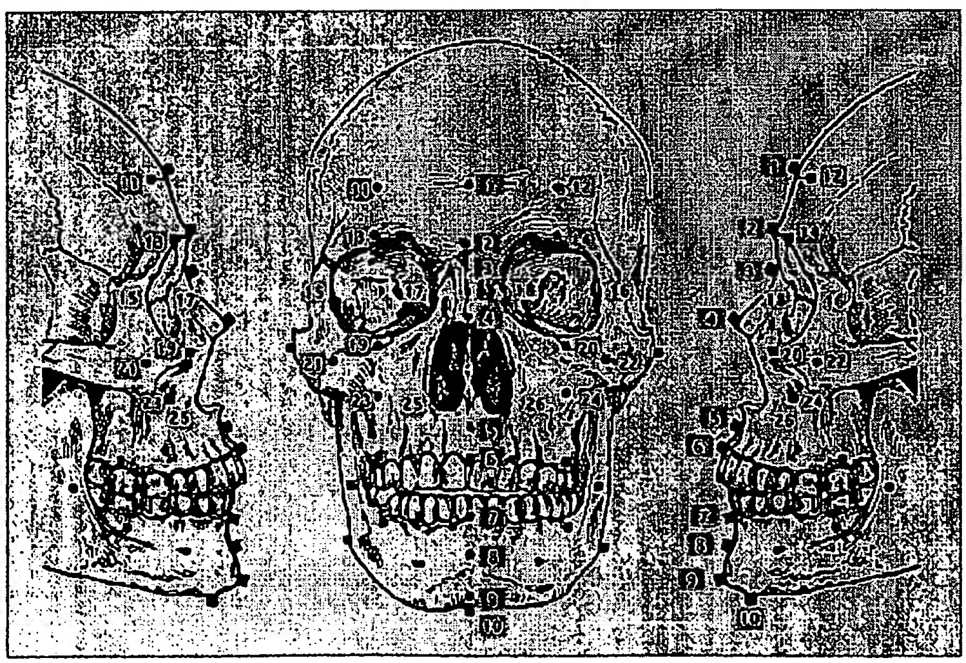

Fig.26 Original points for Manchester protocol

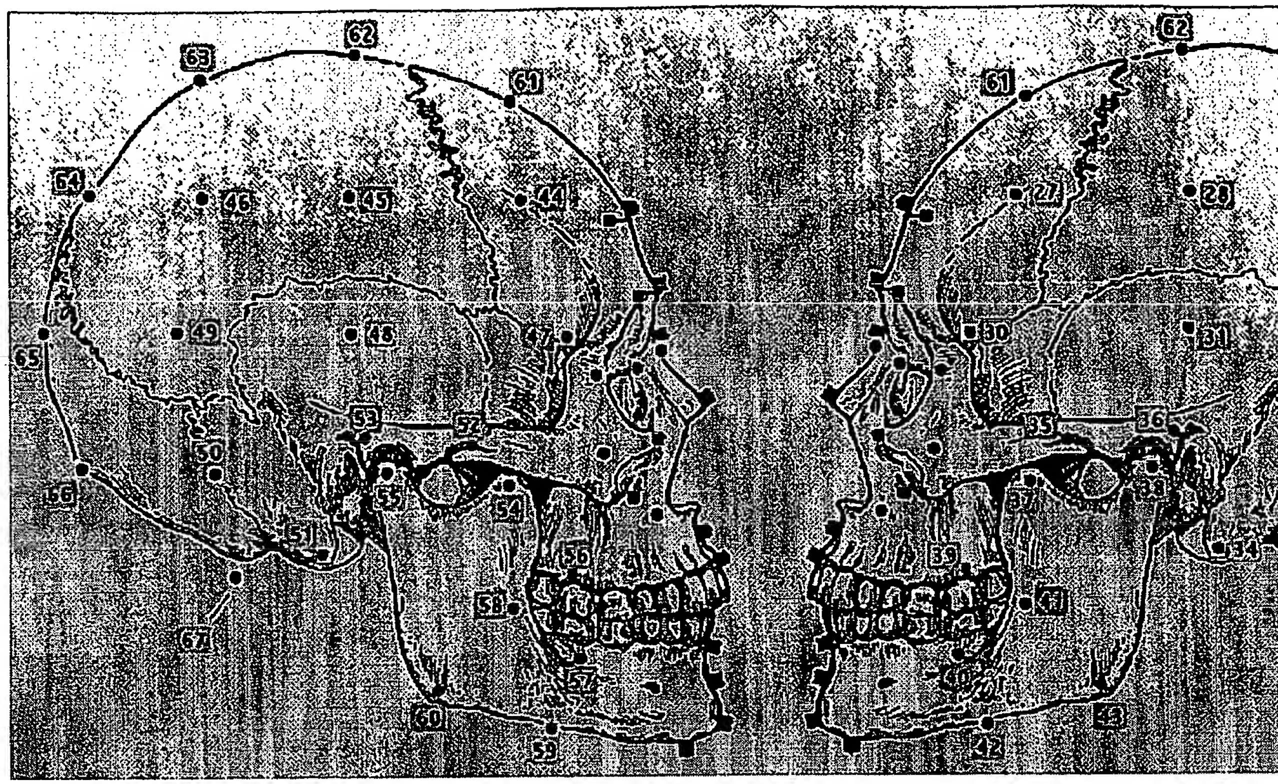

Fig.27 Extended set of points

Appendix B: detail for diffusing scattered fields and warp

Our building block to perform diffusion is the Shepard?s method that is implemented by the vtkShepardMethod filter of the Vtk library.
Shepard?s method is an example of a basis function method , more specifically is an inverse distance weighted interpolation technique that can be written as:

$$F(p) = \frac{\sum_{i=1}^{n} \frac{F_i}{\left|p - p_i\right|^2}}{\sum_{i=1}^{n} \frac{1}{\left|p - p_i\right|^2}} \quad where Fi = F(p_i)$$

To make this filter operate on vector values we write a new Filter that internally instantiate three vtkShepardMethod and let them operate on the single components as show in next figure.

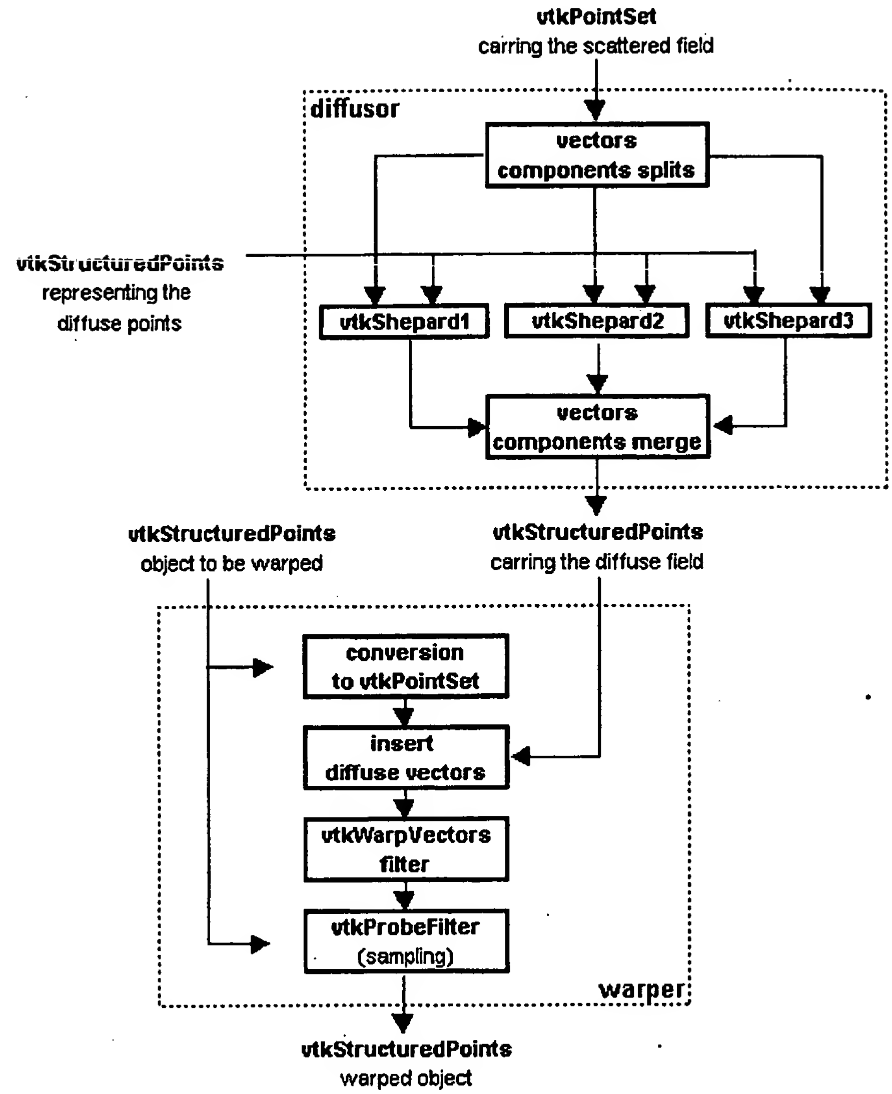

Fig.28

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Newstrack

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Abstract (Document Summary)

Developments in the computer industry among various companies worldwide are discussed.

Full Text (1031 words)

PAY RAISE...Russian president Boris Yeltsin has approved substandial salary increases for top scientists in an effort to stop the brain drain of scientific talent out of his country and strengthen political support within the scientific community. Implemented last month, full members of the Russian Academy of Science receive monthly stipends of 150,000 rubles (approx. $128) on top of their regular salaries. Corresponding members of the academy receive a stipend of half this value. There will also be increases for qualified researchers and for postgraduate students. The regret in the scientific community is that Yeltsin's moves will not be enough to help impoverished Russian scientists, much less abandon their idea of emigration.

TV PRINT OUT...Hewlett Packard has developed a device resembling a thin VCR that will allow users to link a color printer to their television. HP is teaming with Time Warner next April in an experiment based in Orlando Fla., where residents will have wide access to interactive TV services. Participants will be able to print coupons, shopping brochures, or articles retrieved via TVs. The device works only with HP printers and doesn't yet offer photolike quality. People taking part in the Orlando project will be able to use the device without charge; the market price will be about $3,500. HP says the home version must sell for $300 to be a hit.

FLICKERING OPPOSITION...Stabilizing the flicker of computer screens could have the opposite effect on eye strain, according to psychologists. Nature reports screen flickering occurs each time a cathode ray tube refreshes the screen with new information, approximately 50-60 times a second. Increasing this rate to 100 times a second has been suggested to stabilize the screen, therefore alleviating eye strain. The controlled study of how screen flicker directly affects the minute unconscious eye movements used in screen reading suggests eye movements are increasingly disrupted when screen refreshing is raised to the suggested rate.

COMPUTER STATS...Of the more than 90% of the people who say they use a computer at work, Priority Management reports that 18% describe themselves as very computer skilled, 17% say they have basic skills, 29% report they are adequate and 36% say they are inadequate.

LABORATORY EXPERIMENT...Due to financial and organizational problems, an attempt to establish a Japanese version of the M.I.T. Media Lab faces an uncertain future. The project was started in 1987, its goal being to build a research facility outside Tokyo with the creative agenda and style traits associated with the M.I.T. lab. However, Japan's current economic slump has hindered the ability of industries to spend money on advanced research. There has also been reports of a clash over organizational strategy between some Japanese organizers and Nicholas Negroponte, the director of the Media Lab. M.I.T.'s five-year contract with the International Media Research Foundation expired in June 1992 and since then six people have stepped down from the board of directors, including the chair, Tadashi Sasaki, one of Japan's most prominent engineers. The secretary general of the foundation said it still plans to build the laboratory by 1996.

SEARCH TEAM...Veterans can search for old military friends by using a new computerized locator service. VET-FIND Inc., based in Las Vegas, is unique in its ability to identify someone using only a few key pieces of information. For a one-time fee of $35.00 veterans are permanently enrolled in the database and may search for as many as four friends. Unfulfilled searches continue indefinitely and privacy is assured. For more information call 800-838-7787.

E-PORN ARRESTS...Six people have been charged in an ongoing effort by federal law enforcement officials to crack an international pornography ring that has flourished using an electronic bulletin board. Computerworld reports the Denmark-based board, known as Bamse, can be used to download a variety of child-related pornography in the form of graphic images, text, and computer games. More charges are pending as of this writing.

PUT A MUZZLE ON IT...An antinoise generator, a device designed to reduce the sound of buses, is being tested in New York, Houston and two transit systems in Southern California. A computer-driven 220-watt speaker, invented by Noise Cancellation Technologies Inc., Stamford, Conn., is placed in the tailpipe of the vehicle and emits sound waves to partially cancel exhaust noise. But the New York Times reports the electronic muffler is of greater interest to transit officials for its fuel efficiency traits: the technology makes it easier for the bus to emit exhaust which in turn raises horsepower and increases fuel economy. Further muffling technology may eventually be able to quiet transmissions, drivetrains and fans or air-conditioning compressors.

ALL THE RIGHT MOVES...A New York dentist has invented a virtual surgery system that allows oral surgeons to practice delicate operations as many times as necessary. Digitalized data on the patient's teeth, gums and tissues are entered into the system using a wand-like device passed over the surgical site. X-ray findings are incorporated into this mouth map on which the dentist can rehearse.

SORRY, CHARLIE...In a move to protect their property, Avis, Hertz and other car rental companies are using electronic links to government computers to screen potential renters. The electronic checking, which only takes seconds, is turning away 6% to 10% of the people who request cars. Clerks enter the potential renter's name, birth date and driver's license number on the rental company's central computer and it is routed to a company in Queens, NY, which then pulls a public record at the motor vehicle department of the appropriate state. The record is analyzed according to criteria set by the rental company.

SPATIAL CONSIDERATIONS...Finding a legal parking space in New York City requires quick and cunning moves. However, City College engineering supervisor Randolph Archbald went a little too far when he started turning out bogus parking permits using the college's computers and his own sophisticated equipment. He was soon nabbed and charged with counterfeiting police and correction department parking placards. Authorities said Archbald used an expensive laser wand that made it simple to duplicate genuine permits which would allow him to park anywhere (except in front of hydrants and bus stops). Archbald is the first person apprehended for producing fake permits. If convicted, he faces a maximum jail term of 15 years.

VIRTUAL ORTHOPEDIC SURGERY TRAINING ON PERSONAL COMPUTER

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Abstract: Surgical training is one of the most promising areas in medicine where 3-D computer graphics and virtual reality techniques are emerging. This paper provides an advanced report on our project that aims to create virtual reality tools for training medical students and for improving skills and efficiency of orthopedic surgeons in internal fixation of bone fractures. The paper describes the whole pipeline from the CT scanner through the Unix-workstation to the personal computer where eventually the program works. We also describe the methods and mathematical models that allowed us to implement the ultimate goal of the project—to allow the surgeons to perform training surgical operations even at their home computers without any special expensive hardware devices. This project was initiated in co-operation between NTU and SGH and currently continues as an international project.

Keywords: surgery training, virtual reality, orthopedics.

1. Introduction

Surgical training is one of the most promising areas in medicine where 3-D computer graphics and virtual reality techniques are emerging. Attention of researchers has now turned toward using combined 3-D reconstruction and virtual environment (VE) technologies to train clinicians and to help surgeons plan patient-specific, complex procedures in craniofacial reconstruction and plastic surgery, surgery for trauma from accidents, breast cancer detection, and reconstruction surgery.1-6 In surgery simulation for training the clinicians, the benefit of savings in time, cost, equipment, and safety can be enormous. As a result, there is a growing interest in applying VR simulation technology to the medical educational process.

Surgical simulators are used to create a VE wherein the surgeon may simulate and plan the operation, and the surgeons or students can be trained. One of the main problems is to receive a photo-realistic representation of operation room, human body parts from CT or MRI data, surgical instruments and implants. Sound can be imposed into the scene to add realism. For example, sound of drilling has been added in VE of craniofacial surgery simulation.1 Virtual surgery is often performed with tissue and blood.5-8 For example, the training system KISMET7,8 provides simulation techniques, which allow the modeling of "virtual tissue", based on a data-model which reflects the physical characteristics like mass, stiffness and damping of real tissue. However, for orthopedic surgery, it is not necessary to simulate the soft tissue except of some cases in craniofacial surgery. For example, it is important to know the result of bones replacement covered with tissue in craniofacial surgery. When all the reconstruction work is completed, the soft tissues are replaced so that the surgeon can visualize the result. If the outcome of the virtual surgery is not desirable to the surgeon, the virtual

process can be repeated until satisfaction is obtained, without touching the patient. In surgical simulators, a collision test algorithm for detection of the contact between surgical instruments and the virtual organs is often performed. In the training system KISMET[8], contact forces between the tissue and the instrument end-effector are calculated which can be used to drive a force-reflecting surgeon interface 3D-simulation support during the design of new surgical instruments and manipulator.

A comprehensive software system for interactive visualization, manipulation and measurement of multi-modality 3-D medical images has been developed, used and evaluated at the Mayo Clinic for Computer Aided Surgery and Radiation Treatment Planning for more than a decade.[9,10] This software system, called ANALYZE, has provided surgeons and physicians with powerful and flexible computational support both for pre-operative surgical and treatment planning and for post-operative evaluation. The software has been applied to a variety of surgical and medical problems, and used on significant numbers of patients at the Mayo Clinic and at many other institutions.

The training systems available on the market are oriented on solving the particular problems. For example, Limb Trauma Simulator (Musculographics Inc.) models a gunshot wound to the leg for military surgeons training.[11] Software for VR Surgery mainly works on UNIX on Silicon workstations or is prepared on the powerful workstations. For example, Voxel-Man Junior is a subproject of the general VOXEL-MAN-project aiming to transfer substantial functions of exploring and manipulating 3D anatomical models from the workstation based VOXEL-MAN system to inexpensive PCs.[12,13]

In this paper, we address the problem of developing virtual reality tools for training medical students and for improving skills and efficiency of orthopedic surgeons in internal fixation of bone fractures. We developed a desktop VR orthopedic surgery training system capable of running on commonly available PCs including notebooks without compulsory use of VR hardware.

2. The Problem Statement

During common orthopedic surgery training, students must fix fractures on synthetic plastic bones using surgical tools and implants. Fig. 1 shows a typical fractured plastic bone. These synthetic bones differ in quality and cost. Good-quality synthetic bones aren't just simple plastic dummies. They are made from the materials with different densities and textures on the surface and inside to simulate real bones as closely as possible.

Normally, students assemble the bone in front of them, in the position typical of the respective real operation. Then, they reduce the fracture and fix it internally using implants that include hundreds of different plates, screws, nails, and wires. See Fig. 2, for example, where the fractured femur is fixed with the nail inserted in its canal and with four screws. For the insertion of implants, students—or surgeons—use different surgical instruments that let them drill holes, measure for a length, insert the implants, and so forth. The training lab with all this stuff looks rather like a repair shop. There is no flesh and blood there, or anesthesia and assisting nurses. Each student works along independently.

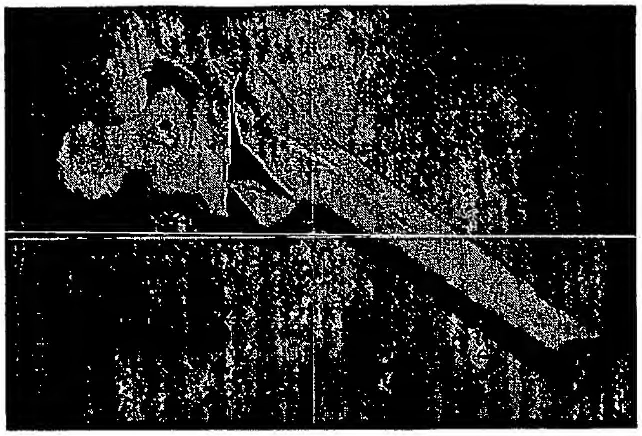


Fig. 1. Fractured synthetic bone.

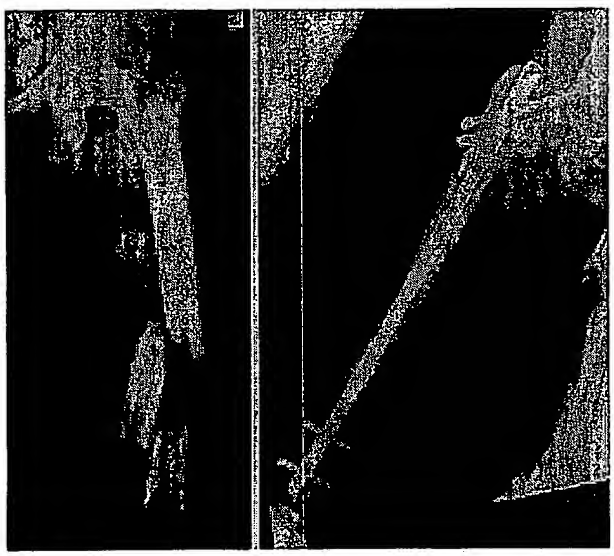


Fig. 2. X-ray of the fracture and its fix.

The objectives of this orthopedic training follow:

- To memorize the techniques and respective tools and implants used for fixing fractures, and to choose the most relevant technique for each case.
- To learn how to put the implants in place, including exactly where and how deep to drill or cut the bone, the proper insertion angle, and so on.
- To acquire "muscle memory " for the physical efforts applied to the tools and implants to avoid damaging the bones.

Many synthetic bones are spoilt before a student can demonstrate the necessary skills on this "synthetic patient." The next step is surgical operations on cadavers. Only after that is the student allowed to approach a real patient.

The idea of using a computer for orthopedic surgery training came from surgeons in the Department of Orthopedics of Singapore General Hospital, who approached the School of Applied Science at Nanyang Technological University (where the first two authors were employed at the time). The surgeons were interested, first, in saving the cost of the bones—good-quality synthetic bones are expensive—and second, in the ability to work with certain types of bones for which synthetic models might not be available. The latter need also derived

from the fact that real Asian bones have their own geometric specifics compared to the commonly available synthetic bones. Besides that, the surgeons anticipated an attractive possibility—training the students on virtual models of real fractures obtained from computed tomography (CT) or magnetic resonance imaging (MRI) data.

Our feasibility study assured us that at least the first two objectives of the common orthopedic training could move into the virtual environment relatively easily, with the outside possibility of complete virtual orthopedic surgery training if special haptic devices were used. Certainly, this virtual training won't substitute completely for the compulsory training on synthetic bones and on cadavers, but it might let the students perform the initial routine work entirely in the virtual environment, thus saving cost and time.

To make this virtual training easily accessible, we decided to develop a software system capable of running on PCs, available in every medical clinic and in homes. This desktop or "pocket" VR system had to produce acceptable realism even without special VR input devices such as head-mounted displays (HMDs) or goggles, although using them obviously would provide better immersion.

Eventually, we came up with a project aiming to develop an inexpensive alternative to common orthopedic surgery training that would allow the surgeons the following:

- To keep in the computer every single bone of different sizes and specific features that might be difficult and expensive to obtain using synthetic models.
- To create models of the fractured bones from real patients using data from CT and MRI images.
- To perform surgical operation planning before undertaking the actual operation.

3. Virtual Orthopedic Surgery Training

First initial reports on this project were published in papers.[14-16] In this paper, we provide an extended report on the project describing the whole pipeline from the CT scanner through the SGI-workstation to the personal computer where eventually the program works. We also describe the methods and mathematical models that we used for implementing the ultimate goal of the project—to allow surgeons to perform virtual surgical operations even at their home computers without any special expensive hardware devices.

Achieving immersion in most VR systems usually requires the following:

1. Realistic 3D geometric models with behavior and constraints.
2. Real-time simulation including collision detection, sounds, and so forth.
3. Real-time 3D rendering.
4. VR rendering and input techniques based on special hardware devices.

Since we aimed to develop a system capable of running on PCs including notebooks without compulsory use of VR hardware, we concentrated on the first three requirements at the current stage of the project. Also, while designing the system, we kept in mind the significant difference between computer-assisted surgery and training systems. The former assist and guide the surgeon during the real surgery operation, while the latter simulate only certain aspects of these operations with a sufficient degree of realism.

In the virtual environment, the orthopedic surgeon deals with models of bones, surgical tools, and implants. Fixing fractures requires using certain virtual fixation techniques. To achieve our goals, we had to find a reasonable balance among the processing time, the size, and the complexity of the models and techniques.

4. The Data Pipeline

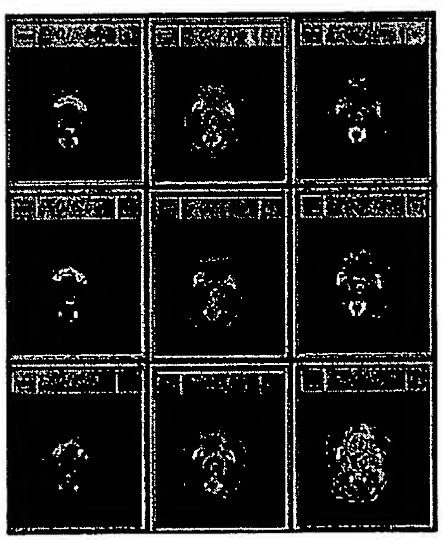
Except for cases where the data for reconstruction of the bones, the tools, and the implants come from the atlases or third parties, the following pipeline was developed for the project.

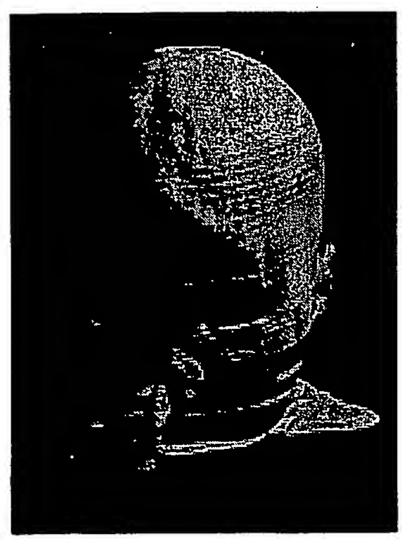
Initially, the CT-images are obtained. Images like those depicted in Fig. 3 are to be delivered to a computer that is responsible for 3D model reconstruction. Normally, these images come in the proprietary data formats and have to be converted in one of the common image formats. In our case, for all these purposes, we used SGI workstations though it could be virtually any *Unix* workstation or *Linux* computer. The choice of SGI workstation was done simply because we planned to use the 3D reconstruction software that was available on it. Actually, the same processes could be implemented entirely on the personal computer.

After the CT images are copied to the workstation, there are basically two ways to work with them.

First, they can be automatically processed by the special software that reconstructs 3D models from the 2D slices. For these purposes, we used the free-ware software *NUAGES* by Bernhard Geiger[18] that creates 3D polygonal meshes from the 2D contours.

Fig. 3. Example of CT-images. Fig. 4. A 3D reconstruction from the images.





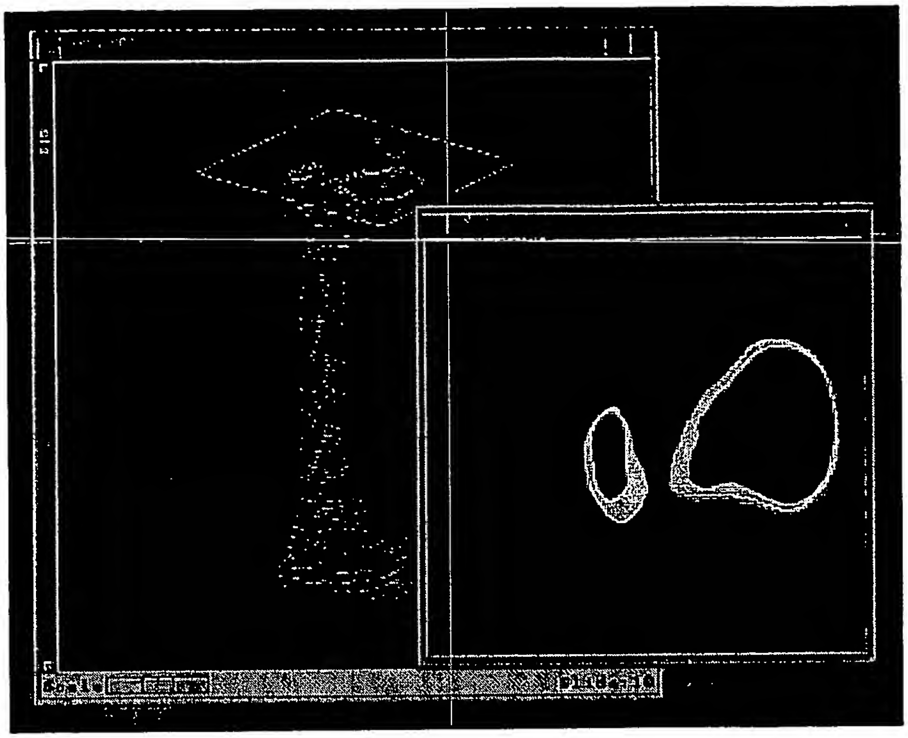


Fig. 5. The interactive 3D modeling tool for extracting and editing contour lines.

Second, for the editing purposes, we developed an interactive 3D tool that builds and edits contour lines for the CT slices and converts them to the data file later processed by *NUAGES*. In Fig. 4, an example of the 3D reconstruction from the data in Fig. 3 is depicted. In Figs. 5 and 6, the 3D editing tool and the reconstructed models of the femur are presented. The 3D data of the bones obtained later are converted to the data format used by our program and then transferred to the personal computer.

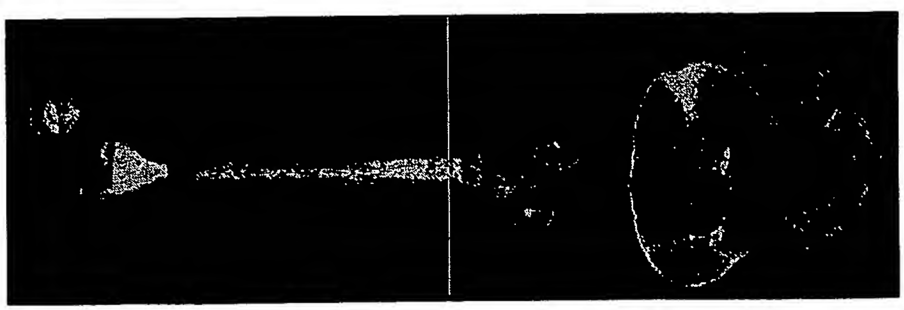


Fig. 6. The reconstructed femur and the femur neck

5. Objects and Operations in the VE

Analyzing the application area, we understood that most bone fractures appear to occur in predictable patterns. For example, there are 27 types of femoral fractures (see Fig. 7) and 9 types of pelvic fractures. This encouraged us to create a geometric database of the fractured bones using geometric models of the broken bones created from standardized geometric models. These bones were "broken" as needed using interactive modeling tools and other methods.

To fix fractures, surgeons use hundreds of different screws, plates, nails, wires, and locking bolts. Their geometric models and the models of the tools were also created and stored in the respective geometric databases (see Fig. 8).

Since the software had to be implemented on a common personal computer, we had to find a reasonable balance between the processing time, the size, and the complexity of the model. Analyzing the goals that must be achieved, probably the straightforward method can be to implement something like the functionally based spatial spline.[19] This spline would interpolate the bones from the scattered points, and for any trial point would answer the question whether the point is inside, outside or on the boundary of the bone. Unfortunately, all these methods, providing a general solution to practically every problem, assume very extensive use of computer memory, and will not provide the required interactivity. Thus, we decided to combine different models for different purposes in our representations.

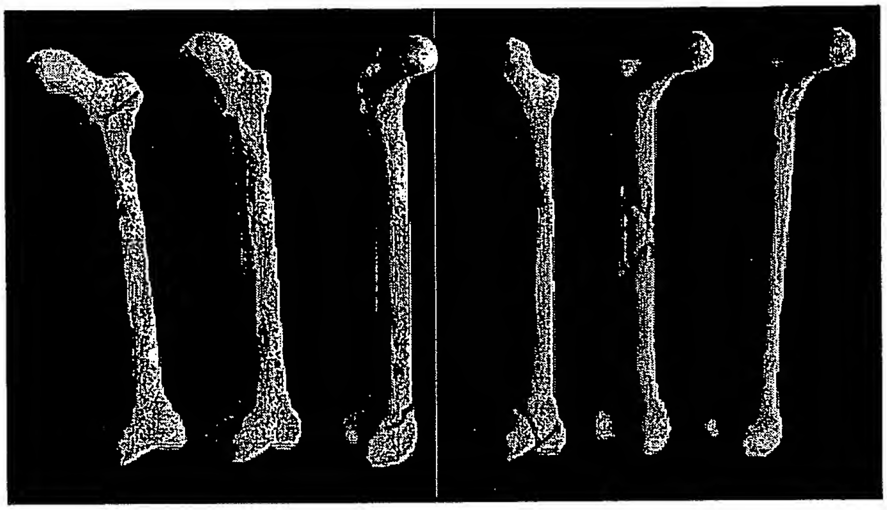


Fig. 7. Several femoral fractures from the geometric database of common fractures implemented for the project.

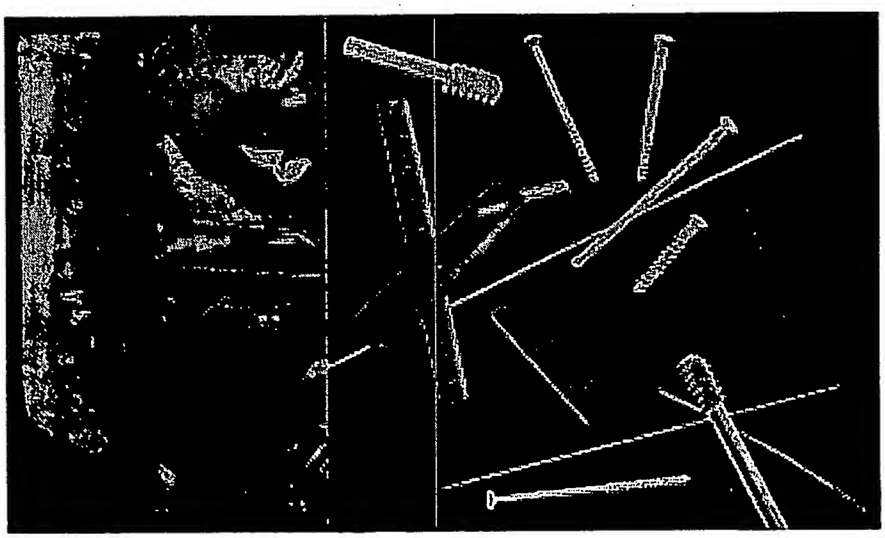


Fig. 8. Real and virtual surgical tools and implants from the geometric database implemented for the project.

Internally, each geometric model in the VE is represented as a polygonal mesh with the functional description that—like geometric DNA—constitutes its shape. Extra application data is stored in the attachment to the geometric model. Thus, for example, extra information about the number, the size, and the locations of the holes for each plate are stored with the polygonal

mesh and functional description of the plate. For the bones, the essential information is the location of their medial axes.

Since the final assembly somewhat resembles complex objects in CAD, each object in the VE and the scenes composed from the objects are stored in the hierarchical geometric database. For example, each plate with holes is a hierarchy of the solid plate body as a root object with the addressable holes as its children nodes. When inserting a screw through the plate, first the surgeon picks up the hole, then the inserted screw becomes yet another child node of this assembly. If the guide wire is inserted through the plate's hole, later it will be used for inserting the cannulated screw. In that case, the coordinate systems of the guide wire and the cannulated screw will be aligned to provide the guiding effect. After the insertion, the guide wire will be removed from the scene, and the screw will substitute for it in the hierarchy.

Many common surgical techniques handle internal fixation of bone fractures, such as fixation with cancellous screws[20], fixation with an intra-medullary nail[21], dynamic condylar screw (DCS) implant system technique[22], dynamic hip screw (DHS) implant system technique[23], and so on. Analyzing them systematically from a geometric point of view, we managed to find common and specific parts that let us come up with the generic virtual fixation techniques that became foundation virtual methods in our project. These methods have been implemented on the internal level, while the surgeon sees the familiar names and commands at the user interface.

6. Collision Detection

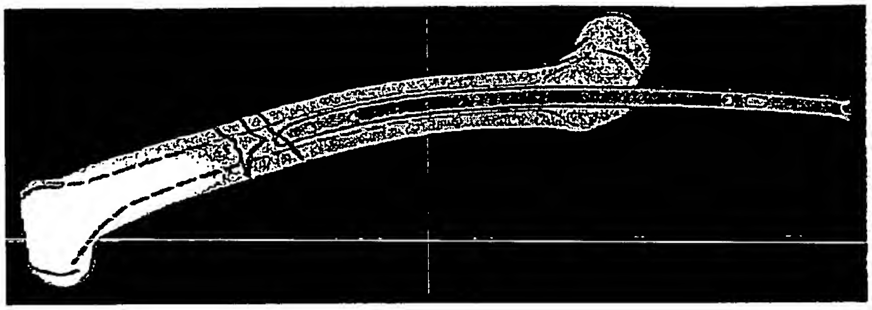
All the geometric and nongeometric data are used together for pseudo-physical collision detection—crucial for VR modeling. Each particular operation required developing its own respective methods and models.

For example, when inserting a screw into bone through a plate's hole, the proximity sensors of each plate implemented as functional fields engage to attract the screw tip to the nearest hole. Then, depending on the mode selected, the screw will either automatically align with the hole axis or the surgeon will have a limited ability to change its orientation, thus simulating the actual insertion of a screw. The screw being inserted never goes through the solid parts of the plate. Since the length of each screw and all the sizes of the plate are among the parameters stored in the geometric database, the screw never penetrates deeper than it should. For the surgeon, the result looks very realistic.

Another example of handling collision detection involves an implementation of nail insertion in the femoral canal (Fig. 9a). The femur with its canal has a curvature of a certain radius. The nail to be inserted (Fig. 9b) is a piece of a large torus with the same curvature as that of the femur.

Mathematically, the problem of insertion is to find the initial location of the torus so that it lies in the same plane with the bone's medial axis and so that its axis is coincident with the axis of the bone curvature. From the surgeon's point of view, the skill required in this operation is to find the proper point and angle of insertion for the nail. These initial parameters let us solve the geometric problem of the axes' coincidence and answer the question whether in principle the nail goes freely all the way through the canal or seriously damages the bone.

These are just two examples of the methods used to solve collision detection problems in our project. Each particular operation required developing its own respective methods and techniques.



(a)

(b)

Fig. 9. Universal femoral nail.

7. Virtual Bone-setter

We called the software implemented in this project Virtual Bone-setter. The program runs on PCs with the most common architecture though the following features are preferred:

- Powerful CPU not less than 150 MHz.
- Extended RAM 64MB or above.
- Video card supporting 3D polygon rendering and real transparency.

Using a mouse as an input device controlling object relocations may suffice, but for some users it might not be as realistic as expected. Better immersion results from using relatively cheap 3D mice or graphics pads instead. The software is implemented with Criterion's Renderware, which provides the required interactivity with a reasonable quality of rendering. Comparing with the *de facto* standard OpenGL, it provides better speed of rendering though slightly sacrificing the rendering quality since it uses less number of bits for representing the colors. The ability of Renderware to model in hierarchical coordinate systems and its support of many VR devices provides a very natural environment for the geometric modeling in the project.

Starting the virtual surgery, the surgeon locates the fractured bone in 3D space looking at the screen. Then, depending on the fracture, the surgeon can issue the following basic commands:

- Applying the instruments and putting the implants in place.
  To simulate the surgical techniques, the following explicit and implicit commands are used: "Insert threaded guide wire", "Insert pin", "Remove threaded guide wire", "Remove pin", "Insert multiple guide wires", "Measure for the screw length", "Insert screw", "Seat plate", "Insert nail", etc. These operations are applied to the current objects in the scene. The user is required to locate the application point on the bone, to define the orientation or to follow the guided orientation, and to apply or to insert the instrument or implant to the proper depth. In common training where expensive non-reusable synthetic bones are operated, it usually takes hours of practicing to achieve the required skills. All the models were created with the maximum possible realism to train the surgeons visually so that they will remember how all this hardware looks before they enter the training lab. Collision detection is implemented to ensure proper insertion of the implants (e.g., for the screws being inserted through the plate holes and for the cannulated screws being inserted by the guiding wires). The screws rotate about their axes when inserted. The speed of insertion slows down when the tension is growing. Drilling and cracking sounds are played for the realistic audio feedback.
- <u>Moving, rotating, and zooming the scene and the objects in the scene.</u>
  The whole scene or individual objects can be moved, rotated or zoomed in any direction.
- <u>Looking at the assembly through the X-ray lens.</u>
  The surgeon often inserts the wires, nails or pins to the appropriate depth under image intensification (X-ray). In the virtual environment, it is provided either for the whole scene or for the particular part of it through the so-called X-ray lens.
- <u>Walking through the bone canal.</u>
  It allows the surgeon to look at the seated implants from inside the bone. This effect can not be achieved during the real surgery and is implemented here for education and control purposes.
- <u>Reversing process.</u>
  If something has been done wrong, the multilevel undo operation can be applied without any damage to the models.
- <u>Setting the lights and the background.</u>
  Different type of lights can be applied for better illumination of the surgical field thus simulating the actual environment in the operation theatre. These can be omni-directional or spot-lights.

The program guides the surgeon through the whole surgery, although the surgeon retains the ability to make independent decisions. Pseudo-physical collision detection is implemented. Realistic sounds play when the instruments are used. The scene with the fracture being fixed can be saved at any time and stored in the hierarchical geometric database for further use. If the surgeon requires an implant not in the database, its model can be created interactively and used immediately. If the surgeon wishes to study a real fracture rather than those stored in the fracture database, its geometric model can be reconstructed from CT data.

8. Examples of Virtual Fracture Fixation

Femoral neck fracture fixation with cancellous screws, as depicted in Fig. 10,requires the following actions:

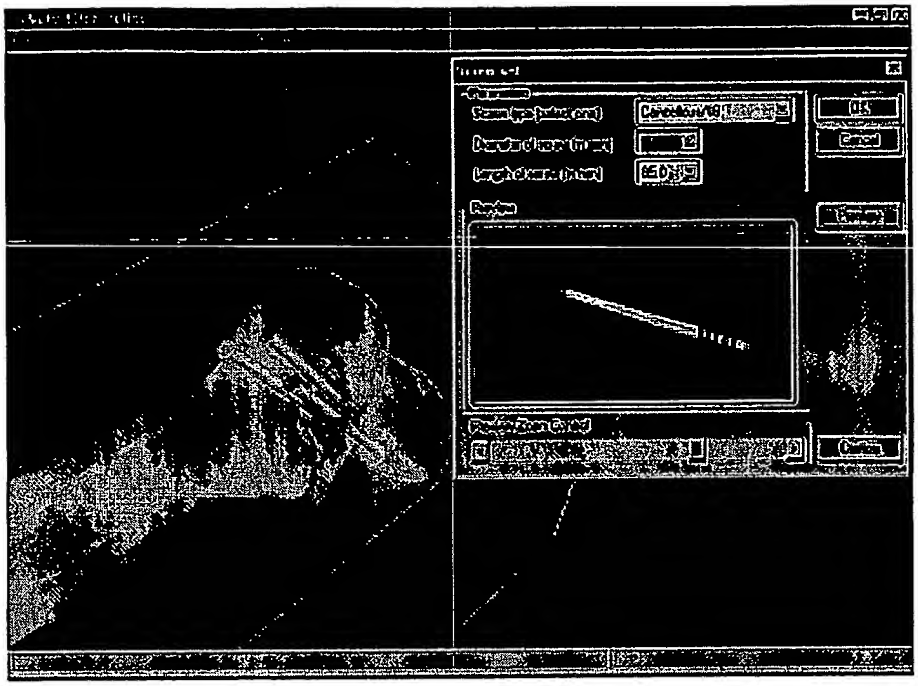


Fig. 10. Virtual femoral neck fracture fixation with cancellous screws.

1. The first step includes guide wire insertion to the appropriate depth. The surgeon chooses "Insert threaded guide wire "and locates the point of insertion on the bone. The wire appears on the screen touching the bone at the selected point. The surgeon rotates the wire to the proper insertion angle and inserts it. The result of the insertion can be checked with the simulated X-ray imaging.
2. The next step is placing multiple parallel guide wires at various distances from the first wire. The surgeon selects "Place multiple guide wires "and defines the respective points on the bone. Wires are inserted automatically parallel to the first one, thus implementing the adjustable parallel wire guide device.
3. Then, the surgeon measures for the screw length. The reading indicates the appropriate screw length. It simulates the result of applying the cannulated screw-measuring device.
4. Next comes inserting the screws. The surgeon selects the cannulated screw of the appropriate length from the database, picks up the wire, and places the screw over the wire. After that, other cannulated screws are placed over the respective wires.
5. The last step is to remove and discard the guide wires.

Another example is the inter-trochanteric fracture fixed with a DHS implant system (see Fig. 11). In this case; the surgeon inserts the guide wire first, next the guide pin, and then removes the wire. The surgeon measures the pin for a screw length and inserts the DHS screw with the appropriate length over the pin. After that, the surgeon seats the appropriate DHS plate over the screw, removes the pin, and fixes the plate with cortex screws through the plate holes. Finally, the surgeon applies the DHS compressing screw to secure the assembly.

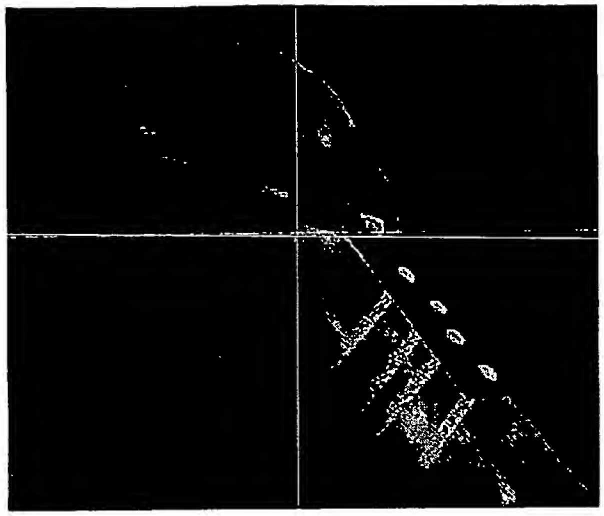


Fig. 11. Virtual femoral neck fracture fixation with DHS implant system.

Yet another example of the virtual femoral fracture fixation with an intra-medullary nail appears in Fig. 12. This VR surgery simulates the real surgery illustrated by the x-rays in Fig. 2 and by the diagram in Fig. 9a. Here, the nail—in fact, a piece of a torus—is to be inserted in the bone canal and then fixed with the screws. This operation requires hours of training before the surgeon learns exactly where to insert the nail and what the insertion angle should be.

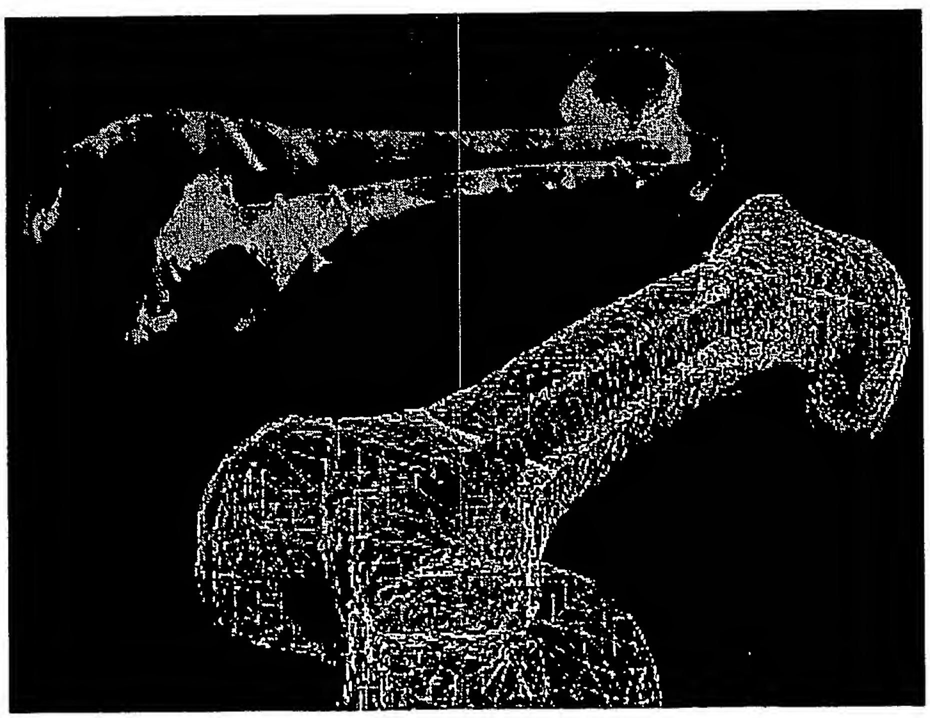


Fig. 12. Virtual femoral fracture fixation with an intra-medullary nail.

9. Conclusion

The implemented tools let surgeons learn how to fix fractured bones and perform preoperative planning without wasting expensive synthetic bones. The software works on common PCs and

simulates surgical techniques, implants, and tools. Using more sophisticated virtual input/output devices, although not compulsory, increases realism and provides better immersion. Besides that, our software also may be used for simulating internal operations for some bone diseases, like slipped capital femoral epiphyses, ankle arthrodeses, sacroiliac joint disruptions, subtalar arthrodeses, and so forth.

The long-term goals of the project follow:

- Photorealistic representation of the operating room environment.
- Force feedback and tactile response using VR haptic devices.
- Object-management at different levels-of-detail.
- Greater immersion, letting the surgeon study and manipulate virtual objects on the screen or on a virtual workbench with a higher degree of realism.

These goals assume software development in both directions—on PCs and advanced software implemented on a virtual workbench. Both lines of software will use the same models and data format, allowing surgeons to handle simple cases on their home or office computers and to ring the most important or complex cases to expensive graphics workstations.

10. Acknowledgements

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